Acidification Experiments in Pine Forests

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Both acid application and NPK increased the acidity of the upper mineral soil. In the humus layer NPK decreased acidity, and the initial acidification by acid decreased with time after the last application (not significant after nine years). Losses of magnesium and calcium occurred in the soil, and foliar analysis confirmed at least qualitatively that the plant availability of magnesium decreased.

Tree growth measurements at Norrliden showed a small but statistically significant increase after application of acid, with the possible exception of the very highest level used. The statistically insignificant reaction at Lisselbo was also a growth increase (for the higher level of acid). Fertiliser addition resulted in a much larger growth response, but with a strong negative interaction with acid, which decreased growth on fertilised plots. As acid deposition in Europe contains both sulphur and nitrogen components, this negative interaction appears to be a very relevant result.

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FÖRSURNINGSFÖRSÖK I TALLBESTÅND.

SAMMANFATTNING

Två långtidsförsök i unga tallbestånd beskrivs, startade 1969 och 1971. I bägge försöken tillfördes under en period årliga doser (två, resp tre nivåer) av utspädd svavelsyra, dels till i övrigt obehandlade försöksparceller, dels till parceller som gödslades med NPK (kväve som ammoniumnitrat årligen, fosfor och kalium med treårsintervall). Gödslingen har fortsatt sedan starten medan försurningsbehandlingen upphörde 1976, eftersom skador på markvegetation hade uppträtt och även andra oönskade biverkningar av bevattning med visserligen utspädd men dock i ekologiskt sammanhang onaturligt stark syra kunde befaras. Avsikten med försöket var ju att etablera försöksytor med olika försurningstillstånd och följa dessa, snarare än att studera effekten på ekosystem av stark syra.

Både syrabehandlingarna och gödslingen ökade surhetsgraden i mineraljorden (0 - 20 cm). I humuslagret minskade gödslingen surhetsgraden, medan syratillsatsen verkade i motsatt riktning, dock med en viss återhämtning så att försurningen vid revision 1985, 9 år efter senaste syratillsatsen, icke längre var statistiskt signifikant. Markförsurningen kunde bl a mätas som sänkning av basmättnaden, med förluster av magnesium och kalcium. Tendenser till sänkt magnesiumhalt i tallbarren kunde också observeras.

Skadorna på markvegetationen efter upprepade syratillsatser har delvis gått tillbaka sedan behandlingarna upphörde. Gödslingen skadade också ris, mossor och lavar, men stimulerade kraftigt kvävegynnade arter som mjölkört och kruståtel. Kombinationen syra och NPK hade en snabbare och kraftigare skadeverkan än vardera behandlingen enbart, men numera är skillnaden i vegetation obetydlig mellan enbart gödslade och gödslade + försurade parceller.

Mätningar av trädtillväxten visade i försöket Norrliden en liten men statistiskt signifikant positiv syraeffekt både vid mätningar på stående provträd och på uttagna borrkärnor. I det senare fallet, som ger noggrannare siffror, ökade dock inte tillväxten vid den starkaste syradoseringen, mätt över hela perioden. På försöksområdet Lisselbo, där antalet syradoseringar och upprepningar var lägre än på Norrliden erhölls inga signifikanta tillväxtförändringar för syratillförsel, men väl en positiv tendens för den högre syradosen. Gödsling ökade tillväxten markant på bägge lokalerna, men särskilt på Norrliden förelåg ett klart negativt samspel mellan syratillförsel och gödsling, så att syra sänkte tillväxten på gödslade parceller (i motsats till på ogödslade).

Tillväxtökningen hos träden för gödsling kan i allt väsentligt ses som en kväveeffekt. Detta bestyrks dels av låga kvävehalter i barren på ogödslade träd (men tillfredställande halter av övriga makronäringsämnen), dels av resultaten från andra försök på samma lokaler med kväve och andra växtnäringsämnen i olika kombinationer. Det förefaller emellertid som om kväveeffekten i viss mån är övergående: sedan beståndet slutit sig är skillnaderna små i tillväxthastighet mellan enbart gödslade parceller och kontrollytor.

Den svaga positiva tillväxtreaktionen på syratillförsel tolkas som beroende på minskad konkurrens om kvävet för trädrötterna från markvegetation och mikroorganismer. Dessa senares aktivitet sänks i laboratorieförsök vid tillsatser av försurande ämnen.

På senare tid har man försökt att definiera "kritisk syratillförsel" ("critical load"), den mängd syra som ett ekosystem kan ta emot utan att drabbas av allvarliga rubbningar av näringsomsättning och organismliv. Om den sämre tillväxten vid den högsta syragivan på Norrliden (jämfört med lägre syragivor) är det riktiga resultatet (den framkom vid de noggranna mätningarna av grundytetillväxten på borrkärnor, medan mätningarna i fält ännu ej visat någon nedgång), ligger den "kritiska syratillförseln" på denna lokal någonstans i närheten av behandlingen "Syra 2", vilket motsvarar 600 kg koncentrerad svavelsyra per hektar eller 1,3 mol vätejoner per kvadratmeter, en siffra att jämföra med ur vittringsberäkningar uppskattade värden på 20 - 50 mmol vätejoner per år och kvadratmeter för marker med normal urbergsmorän. Med en årlig deposition på 20 till 50 mmol tar det 65 till 25 år att uppnå en ackumulerad deposition av 1,3 mol, en helt rimlig siffra med tanke på de markförändringar som observerats bl a i södra Sverige, där den samlade antropogena syradepositionen ofta kan beräknas ha överskridit denna gräns.

Det kanske viktigaste försöksresultat är det starka negativa samspelet mellan syratillförsel och gödsling, innebärande negativa effekter även av "syra 2" vid samtidig tillförsel av ammoniumnitrat. Eftersom luftföroreningssituationen i Europa innebär samtidig deposition av både svavel- och kväveföreningar är detta resultat viktigt.

SUMMARY AND CONCLUSIONS

Two factorial experiments in young pine forest are described, started in 1969 and 1971, respectively. In both experiments sulphuric acid in different amounts was applied annually to plots which either got no other treatment or received NPK fertiliser (nitrogen as ammonium nitrate annually, PK at three-year intervals). The fertilizer additions have continued since the start, while the acid applications ended in 1976 in order to study effects of changed soil conditions rather than possible artifacts from addition of relatively strong acid.

Both acid application and NPK increased the acidity of the upper mineral soil. In the humus layer NPK decreased acidity, and the initial acidification by acid decreased with time after the last application (not significant after nine years). Losses of magnesium and calcium occurred in the soil, and foliar analysis confirmed at least qualitatively that the plant availability of magnesium decreased.

Ground vegetation was damaged by repeated acid applications, but has partly recovered since the end of the applications. Fertilization also damaged dwarf shrubs, mosses and lichens but favoured nitrophilous species such as Deschampsia flexuosa and Epilobium angustifolium.

At Norrliden, measurements of tree growth showed a small but statistically significant increase after application of acid, with the exception of the highest level used. The statistically insignificant reaction at Lisselbo was also a growth increase (for the higher level of acid). Fertiliser addition resulted in a much larger growth response, but with a strong negative interaction with acid, which decreased growth on fertilised plots.

The positive tree growth reaction for fertiliser addition is caused mainly by the nitrogen compound of the fertiliser as witnessed by the low levels of available nitrogen in both soil and needles of unfertilised plots. Other experiments with nitrogen and PK fertiliser on the two sites corroborate this. However, it appears that the growth effect of nitrogen is temporary; after canopy closure there is not much difference in growth-rate between fertilised and unfertilised plots without acid.

The weak positive tree growth reaction to acid is explained as due to decreasing competition from lesser vegetation and soil microorganisms, the activity of which is depressed in short-term laboratory experiments. If the depression in basal area

growth found in treatment Acid 3 is real (the present slight discrepancy between measurements of basal area growth on increment cores and of stem volume growth on standing trees should be reexamined after the next field revision), the critical load of sulphur can be set to approximately "Acid 2", which means 600 kg of sulphuric acid per hectare or 1.3 mole of charge per square metre.

The most interesting result obtained seems to be the strong negative interaction between acid and fertiliser, implying that also "Acid 2" has negative growth effect, when applied together with ammonium nitrate. As air pollution in Europe contains both sulphur and nitrogen compounds, this result appears very relevant.

1. INTRODUCTION

The possibility of negative ecological effects of acid rain on a regional scale in Europe was first suggested by Svante Odén in the late 1960's (Odén, 1968). As most coniferous forests in northern Europe have strongly acid top soils, it seemed likely that impacts on such forests, if any, should be indirect rather than direct, affecting nutrient cycling and nutrient availability.

The Section of Forest Ecology at the Swedish College of Forestry (now part of the Department of Ecology and Environmental Research of the Swedish University of Agricultural Sciences) started a series of extensive forest fertilisation experiments during the period 1967-1974, the "Optimum Nutrition Experiments in Forest Stands" and it seemed natural to include some treatments with acids in the experiments laid out from 1969 onwards. The first trial was a rather crude pilot experiment, intended to explore whether such experimentation was meaningful at all.

It was found that the trees appeared undamaged by the treatments, while the lesser vegetation suffered from the contact with the dilute sulphuric acid. The extent of the injuries appeared to depend on the weather conditions following the treatment. Some soil changes (decrease in pH and base saturation) were soon observed, and increased with repeated treatment. From 1977 it has been possible to run the acidification plots as a separate project, supported by the Swedish Environmental Protection Board. There have also been a number of soil biology and soil fauna studies carried out on the plots, mostly as separate projects.

As mentioned above, the basic assumption behind our acidification experiment was that acid deposition might change nutrient availability to trees, and that this was a testable hypothesis. Odén suggested at an early stage (1968) that the acid deposition might deplete forest soils of metal ions and made some calculations of the rate of this process. As there is a fairly general trend that base-rich soils are more fertile than base-depleted ones (other factors being equal), such a process might lead to site deterioration (Dahl & Skre, 1971).

However, in Sweden there is overwhelming evidence that the plant nutrient most often limiting forest growth on normal pine and spruce sites is nitrogen rather than base cations or other plant nutrients. Consequently, it was deemed urgent to test the effect of acidification at two levels of nutrition: normal level and an elevated level with regular additions of NPK, eliminating or at least decreasing the role of

these elements as limiting factors. It was also considered important to extend the manipulation of soil acidity over a wider range than just a limited increase of acidity. The limed plots within the experiments provided this possibility, and liming was also tested at the two levels of nutrition in the experiments described here.

Already at the start of the experiments we were aware of possible artifacts caused by the treatment with relatively strong sulphuric acid watered out one to three times per vegetation period. Yet the moderate (though later increasing) damage to the lesser vegetation and the absence of visible impact on the trees encouraged us to continue the treatments over several years. In two experiments in spruce stands we also used sulphur powder as acidifier (Tamm & Popovic, in prep.).

In 1976 the acidification experiments had been running for eight and six years, respectively, and the highest acid input corresponded to approximately 250 and 300 kg per hectare of sulphur, 20-30 times the estimated annual input with wet and dry deposition in South Sweden at that time. Soil sampling in two of the areas showed that the top soil had been acidified to some extent. It was then considered best to stop further acidification, at least temporarily, and to study the after-effects of the treatments on soil chemistry, soil biology, and tree growth. As the trees appeared to be little affected by the acidification treatments (but greatly stimulated by the fertilisation), it was expected that the ecosystem, including soil microorganisms, would adjust to the experimentally changed soil chemical conditions. Growth measurements and various samplings during a subsequent period would then reflect the conditions in soils exposed to acid deposition in a better way than during the period over which the acid or sulphur was supplied.

The questions we shall discuss in this paper are the following:

1. In which respects has the soil chemistry changed as a consequence of treatments used?

2. To what extent does tree growth differ between control plots on one hand and plots with changed acidity or nutrient regime on the other? Can growth changes be related to soil changes or to changes in nutrient status of the trees as measured by foliar analysis? Are there interactions between acidity and nutrition?

3. What other biological processes, e.g. in field vegetation or soil biota, have been changed by the treatments, and do such changes explain some of the changes in tree growth?

4. If biological effects of the acidification treatments are found, how do these effects develop with time?

5. How do our results compare with those of other acidification experiments, particularly the Norwegian ones which where started only shortly after ours?

Most of the evidence for changes in soil and stand characteristics is presented here in diagrams and Tables, but we also refer to material already published, particularly concerning soil biology changes. There is still material from the experiments which has not been fully exploited because of resource limitations. The long time-scale for changes in ecosystem behaviour makes it desirable to keep at least the Norrliden experiment under further observation. The Lisselbo experiment is considered closed since several plots, mostly non-fertilised ones, have suffered from serious snow and wind damage.

As the first experiment established, E 42 Lisselbo, was of a pilot character, we shall discuss the technically more satisfactory Norrliden experiment (E 57) first.

Fig.2.1.
Location of the pine forest acidification experiments in Sweden.

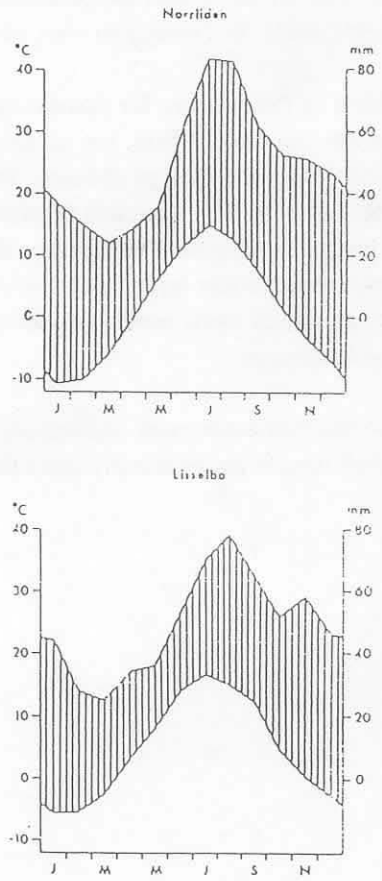


Fig.2.2.
Climate diagram (cf. Walter & Lieth 1967) for the sites **Norrliden** and **Lisselbo.**
Lower curve: mean monthly temperature, for the period 1931-1960; upper curve: mean monthly precipitation for the same period, estimated from standard meteorological stations in the neighbourhood.

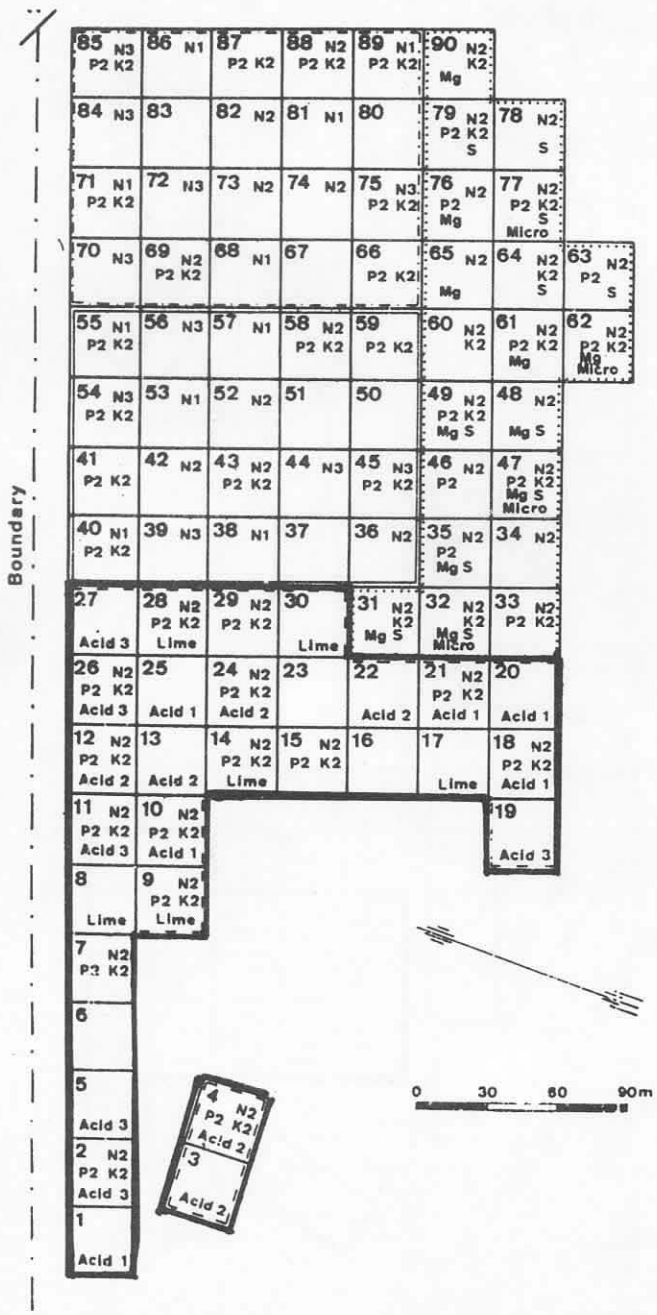


Fig. 2.3. Plan of the **Norrliden** site, located 1 km NW of the village Norrliden and 67 km NW of Umeå. The acidification experiment E 57 is surrounded by a thick line.

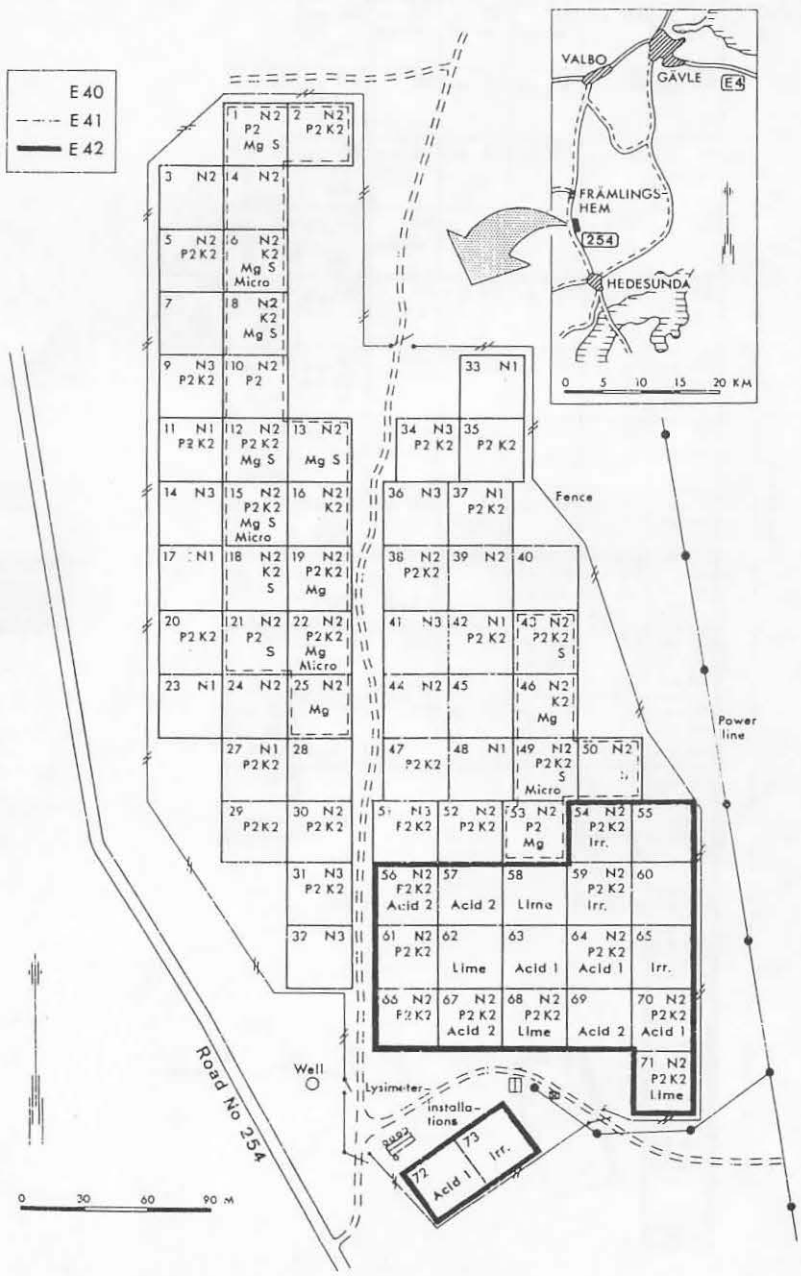


Fig. 2.4. Plan of the **Lisselbo** site, located 22 km SW of Gävle. Plots belonging to the acidification experiment E 42 is surrounded by thick line.

2. SITES AND METHODS

2.1. Site description.

The experiment **E57 Norrliden** is situated north of the river Vindelälven, 67 km northwest of the town of Umeå, on a relatively flat plateau of glacial till at an altitude of 260 m, above the highest coastline after the latest glaciation (Table 2.1).

The soil material is till, with fine sand as the dominating fraction (Fig 3.1,3.2). The soil profile is a typical iron podzol (Holmen et al. 1976), orthic podzol according to FAO-UNESCO (1985). The stoniness index (sect.2.3.1) varies from 20.2 to 28.0 (means of 25 points per plot). According to Viro (1952), this corresponds to stone percentages ranging from 34.2 to 8.7.

The experimental area had been covered with old Norway spruce (Picea abies) -dominated forest, which was cut down in 1951. In the following year, the clearfelled area was subjected to controlled burning. The Scots pine (Pinus sylvestris) stand was planted in 1953 with two-year-old transplants. The planting was successful and there are no large gaps within net plots, even if there is some variation in numbers of stems. A space regulation was done before the treatments started (1970). At the start of the treatments in 1971, the mean height of the trees was 4.9 m. There are a few other tree species (spruce, birch) on some plots; in the measurements they have been included in the volume but they never exceeded a small fraction of the pine numbers and volumes.

Table 2.1. Geographical data for the pine forest acidification experiments and mean annual temperature and annual precipitation (estimated from nearby stations). Average for the period 1931-1960. Wet deposition data from Monitor (1986).

Experiment	Latitude	Longitude	Altitude m	Mean temp. °C	Mean prec. mm	Wet deposition of sulphur S kg/ha/year
E57 Norrliden	64°21'N	15°40'E	260	1.6	595	ca 5
E42 Lisselbo	60°28'N	16°57'E	80	4.8	593	ca 6

The experiment E42 **Lisselbo** is located on a rather low glacifluvial esker and its slope towards the west about 80 meters above sea level 100 km north of Uppsala (Table 2.1). The area is below the postglacial coastline and wave action during the land upheaval has redeposited much of the esker material. The soil is well drained with the groundwater depth varying from a few m in the lowest part to about ten meters. The dominating fraction of the soil material is sand (medium to coarse, Fig 4.2), with increasing frequency of stones along the ridge of the esker and some admixture of fine sand in the lower part. The soil profile is an orthic podzol although with irregular and mostly shallow A_2 horizon, as often found on pine sites with coarse-textured sediments. The stoniness index (sect.2.3.1) varies from 10.0 to 30.0 (means of 25 points per plot). According to Viro (1952), this corresponds to stone percentages ranging from 67.3 to 2.2.

The earlier stand was destroyed by a storm in early 1954, which took down about one--third of the standing forest volume in the parish of Hedesunda where Lisselbo is situated. The spacing of the young stand, consisting of both naturally regenerated and sown pine, was regulated in 1965 by cutting a number of saplings. The number of selfsown spruce and birch is very low.

2.2. Experimental design and treatments.

The **Norrliden** experiment E57 started in 1971. Other experiments on the same site were designed to study effects of various nutrients and their interaction (Holmen et al., 1976; Tamm, 1985). In experiment E57 three dosages of acid were given. Altogether 30 plots 30 x 30 m were used, divided into three blocks. Net plot size was 20 x 20 m. The acidification was achieved by application of dilute sulphuric acid given in a solution containing 0.8 % H_2SO_4 (by weight) followed by the same quantity of water sprayed out over the ground in early summer. Each square metre received each year around 2 l of dilute acid and 2 l water with treatment Acid 3. Nitrogen was given annually as ammonium nitrate, and PK as a commercial PK-fertiliser at three-year intervals. Lime was given as ground limestone at the start in 1971.

The field experiment at **Lisselbo** started in 1969 and the area assigned for experiment E42 was divided into two blocks, each with ten plots 30 x 30 m (net plots 20 x 20 m). The application of dilute sulphuric acid was carried out in the same way as at Norrliden. As at Norrliden, other experiments with different nutrient combinations were also started at the same time (Tamm et al., 1974; Tamm 1985). Four plots of experiment E42, two with and two without NPK were irrigated with the intention of relieving effects of prolonged summer drought. At Norrliden, irrigation was done in a separate experiment (E58). The fertilisers used were the same as at Norrliden.

Table 2.2. Experiment **E57 Norrliden**. Total application of acid and fertilisers.

Treatment	Added S (kg/ha) As H_2SO_4 1971 -1976	As PK-fertiliser 1971- -1985*	Total amount 1971-85 (kg/ha) N	P	K	Ca
Control	-	-	-	-	-	-
Acid 1	98	-	-	-	-	-
Acid 2	196	-	-	-	-	-
Acid 3	294	-	-	-	-	-
Lime	-	-	-	-	-	2 000
N2P2K2	-	196	1 140	220	384	572
" + Ac 1	98	196	1 140	220	384	572
" + Ac 2	196	196	1 140	220	384	572
" + Ac 3	294	196	1 140	220	384	572
" + Lime	-	196	1 140	220	384	2 572

* SO_4-S content in PK-fertiliser (1971, 1974, 1977, 1980 and 1983).

PK-fertiliser: Supra PK 7:13 with 6.8 % P, 13.3 % K, 16 % Ca, 9 % S, 13 % Cl

Table 2.3. Experiment **E42 Lisselbo.** Total application of acid and fertilisers.

Treatment 1969	Added S kg/ha As H_2SO_4 1969 -1976	As PK-fertilisers -1985*	Total amount 1969-85 (kg/ha) N	P	K	Ca
Control	-	-	-	-	-	-
Irrigation**	-	-	-	-	-	-
Acid 1***	114	-	-	-	-	-
Acid 2	245	-	-	-	-	-
Lime	-	-	-	-	-	2 000
N2P2K2	-	216	1 040	220	426	572
" + irrig.**	-	216	1 040	220	426	572
" + Ac 1***	114	216	1 040	220	426	572
" + Ac 2	245	216	1 040	220	426	572
" + Lime	-	216	1 040	220	426	2 572

* SO_4-S content in PK-fertilisers, applied in 1969,1972,1975,1977,1980 and 1983.
** irrigation during dry summer periods in 1970-76, altogether 420 mm.
*** treatment Ac 1 started in 1970.

2.3. Soil sampling and analysis

2.3.1. Field procedure.

Soil samplings were carried out at different times after the start of the experiment at the experimental areas; at Lisselbo in 1971, 1976 and 1985, at Norrliden in 1974 and 1985. The soil samples were collected in a regular pattern along the diagonals of the plots using an auger ("area estimated" samples). The 18-20 individual samples were bulked into one composite sample per plot. The diameter of the auger was 70 mm. The latest mineral soil samplings at the Lisselbo and Norrliden experiments in 1985, were conducted by a special auger (diameter 34 mm with a lateral orifice). The weight data from the auger samplings were used for calculation of humus layer weight, while mineral soil weights were taken from the stoniness index, as described below.

The stoniness index ($Si_{30}cm$) was determined for all plots of the Norrliden and Lisselbo experiments by the rod testing method (Viro, 1952). Viro used the rod method to produce an index value, related to site index. We have compared the rod testing values with actual amounts of the soil fraction < 2 mm by first taking five rod values in a microplot 20x20 cm, then digging down to 20 cm in the mineral soil, sieving and weighing the material and measuring the volume of the soil pit (water volume). The result is presented in Fig 2.5 and can be used to convert the stoniness index to weight < 2 mm per hectare. Most of the data in Fig 2.5 are from the acidification experiments E57 and E63, and there were no statistically significant differences in slope and intercept between the sites studied. Nor did we find any particular difference in bulk density between the three mineral soil horizons studied (0-5, 5-10, and 10-20 cm). The scattering is considerable ($R^2=0.64$) even if it should be remembered that each point in Fig.2.5 is based upon five rod tests instead of 25 in the case of plot data. In any case, the values of soil weight for individual plots must be considered as approximate, although there is a higher accuracy for treatment means than for single plots.

The determination of humus layer weights (and thus all data on chemical contents per unit area) has also a considerable standard deviation. As we do not have replicated samplings from the same date, as recommended by Falck (1973), we compared the plot data on amounts of nitrogen in kg per hectare at the Lisselbo samplings in 1971, 1976 and 1985 (cf. Tables 4.2, 4.3 and 8.18). All three samplings give reasonably similar estimates of the amounts of nitrogen (410 - 450 kg per hectare as a mean value for

the entire experiment). However, the correlation betwen values for individual plots in 1971 and 1976, and also between 1971 and 1985 is low (r values of 0.35 and 0.24, respectively). The correlation between 1976 and 1985 is better, r=0.69**. The corresponding value at Norrliden (comparison between samplings in 1974 and 1984) is also 0.69^{**} (0.72^{**} if calculated within groups of on one hand fertilized, on the other hand unfertilized plots). Apparently, estimates for single plots have a considerable standard deviation, and conclusions can only be drawn for groups of plots or treatments. We consider the 1985 data as somewhat more reliable than the earlier ones, as they were part of a larger sampling procedure, done by the same person, while the 1971 and 1976 samplings only aimed at getting rough estimates as to the order of magnitude of the nitrogen turnover. In the 1971 sampling there was also a shift in sampling persons between different plots.

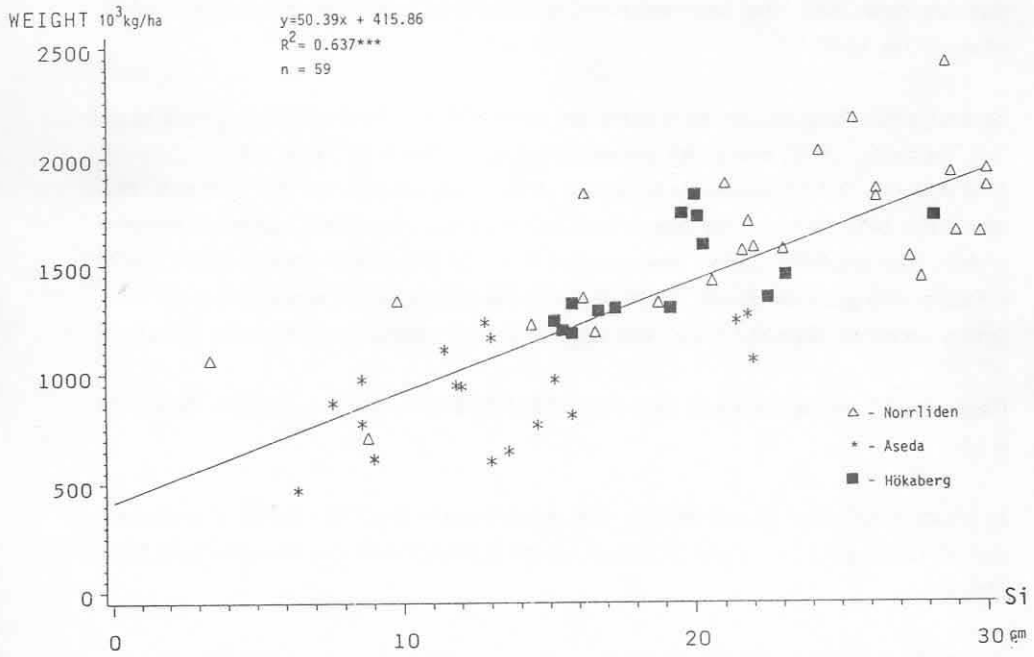


Fig. 2.5. Dry weight of soil material <2 mm plotted against the stoniness index as determined by five rod probings on a microplot 2 dm x 2 dm, later excavated to 2 dm depth, sieved and weighed. The Norrliden data are from Expt **E57** and the Åseda data from another acidification experiment, **E63**. Hökaberg is an optimum nitrogen experiment running 1957-1970.

2.3.2. Analytical methods.

Humus and mineral soil samples were well mixed and sieved fresh; screen mesh 3 mm for humus and 2 mm for mineral soil.

The pH-values were estimated after 24 hours in water suspension (in volume relation 1:3 for humus and 1:2 for mineral soil, roughly corresponding to sample:water weight relations of 1:5 and 1:3, respectively).

Loss on ignition was determined at 550 ^{o}C and carbon calculated by multiplication by 0.58 for humus samples (before 1985, see below). The total nitrogen content was determined according to the Kjeldahl digestion procedure, with measurement on the autoanalyser (sampling series before 1985). Total carbon and total nitrogen in samples since 1985 have been estimated on the Carlo Erba nitrogen/carbon/sulphur analyser Na 1500.

Exchangeable base cations were extracted with 1 M NH_4Ac solution (adjusted to pH 7.0, Balsberg, 1975) except for the sampling at Norrliden in 1974, where 1 M NH_4Cl - 0.1 M imidazole buffering solution adjusted to pH 7.0 (Nömmik,1974) was used. The base cations were determined on an atomic absorption spectrophotometer (AAS). The titratable acidity was obtained from the pH-measurements on the buffer solution with glass electrode. From base cations and titratable acidity, data on cation exchange capacity (CEC) and degree of base saturation (V%) were calculated.

Exchangeable aluminium was extracted with 1 M KCl solution and measured on the AAS.

Extractable sulphate in soil samples was determined in 0.01 M calcium phosphate extract (Sinclaire, 1972) and measured on the ICP emission spectrometer type Plasma 200.

Soil texture was estimated in Na-pyrophosphate solution by wet sieving for fractions 2 to 0.06 mm and by the hydrometer method for the fraction $<$ 0.06 mm (Talme & Almén, 1975). Base mineral index was estimated in the medium sand fraction (0.2-0.6 mm) according to O.Tamm (1934).

Ammonium and nitrate nitrogen were extracted by shaking fresh soil material with 1 % $KAl(SO_4)_2$ solution. The ammonium nitrogen was coloured by indophenol and the blue

colour measured on the autoanalyser (Selmer-Olsen, 1971). The nitrate was reduced with cadmium amalgam to nitrite and measured on the autoanalyser (Popovic, 1977).

2.3.3. Incubation experiments.

The incubation experiments were performed at a temperature of 20 °C in 300 ml Erlenmayer flasks with 40 g of fresh soil material after sieving and adjustment of the moisture content to 60 per cent WHC (water holding capacity) for periods of six and nine weeks with duplicate flasks for each period (Popovic, 1971, 1977, 1984). The flasks were sealed with very thin polyethylene film permeable to O_2 and CO_2 (Bremner & Douglas, 1971).

Incubation experiments were conducted in 1971 and 1976 for Lisselbo, and 1974 for Norrliden. Replicate samples were incubated in special flasks for measuring CO_2-evolution according to the technique described by Nömmik (1971).

2.4. Needle analysis.

2.4.1. Sampling of needles.

During the experimental period the needles were sampled in October from the same ten representative trees each year on each plot. Upon sampling, one to two well-exposed branches were cut from the uppermost part of the crown. The current shoots were separated from older shoots by cutting. The pine needles were removed from the fresh shoots and dried at 70 °C.

2.4.2. Analytical methods

For chemical analysis needle samples were wet combusted in a solution of nitric acid / perchloric acid (ratio 2.5 : 1.0). In the solution, potassium, calcium and magnesium were determined on the flame-photometer (until 1970) on the atomic absorption spectrometer (1971-1984) or on the ICP emission spectrometer type Plasma 200 (after 1984).

Phosphorus and manganese were determined colorimetrically, until 1984 and then on the ICP emission spectrometer Plasma 200. Sulphur, aluminium and microelements were analysed on the ICP emission spectrometer.

Fig. 2.6. The boundary between the **Norrliden** experimental area and an area with seed trees N of the experiment (right). Photo from 1969, before the experiment was laid out, but the pines in the left margin should belong to plot No. 1 or 2.

Fig. 2.7. The **Lisselbo** experimental area. April 1969.

Nitrogen in needles was determined according to the Kjeldahl procedure, with distillation and titration up to 1977; after 1977 they were measured on the autoanalyser after dilution of the Kjeldahl digestion acid.

2.5 Vegetation studies.

Qualitative observations on vegetation damage have been made from time to time, the most detailed being in August 1976 at Norrliden. In 1987 (Lisselbo) and 1988 (Norrliden) a detailed vegetation survey was made by G.Dirkse and H. van Dobben, Research Institute for Nature Management (RIN) Leersum, Netherlands. The results will be reported in a separate publication. Therefore the text here will only report results from the qualitative observations, partly in connection with photographs.

2.6. Tree growth measurements.

All tree stands on the sample plots were measured in the same way as the permanent yield plots of the Yield Research Department. This means numbering of all trees above breast height within the net plots, and measuring breast height diameter (d.b.h., by cross calipering at permanent marks on the stem) and height at intervals. The height measurements comprised all trees in very young stands, every second tree plus the few dominant trees after canopy closure. A few trees not reaching breast height at the first measurement, but considered likely to become part of the future canopy, were also numbered and measured for height. The intervals between stand measurements were 3 to 5 years.

Volume estimates were made from these measurements, using formulas from Näslund (1940-41 and 1947, Norrliden and Lisselbo, respectively) and Andersson (1954, for small trees) for volumes calculated on individual stems or mean trees for diameter classes.

As volume estimates from repeated stand measurements, particularly with short intervals, inevitably have considerable measuring errors, it was planned to measure also annual ring growth on cores or stem sections. Yet this has only been done at Experiment E57 Norrliden, where the stand consists of pines that are large enough to be bored. The cores were measured with the standard procedure of the Institute for Forest Improvement, which allows calculation of basal area (primarily under bark) in different years.

Some of the details in the tree measurements will be further discussed in later sections in connection with the data presented.

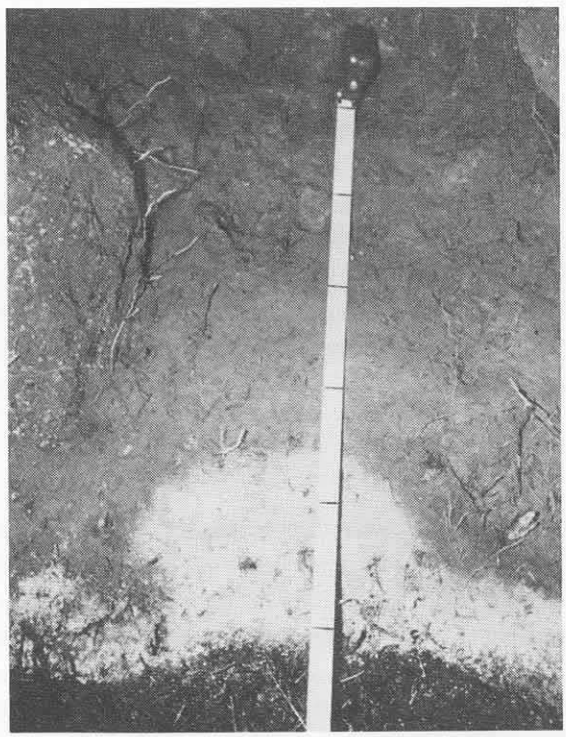


Fig. 2.8. Typical soil profile, **Norrliden**.
The length of the tape is 60 cm.

3. EXPERIMENT E 57 NORRLIDEN.

Results and discussion

3.1. Soil analyses and incubation experiments.

As mentioned in Section 2, the Norrliden experiment is situated on a site covered with glacial till, located above the highest coastline after the glaciation. The experimental area is fairly level, with the topographical gradients within plots mostly below two metres. Most of the experiment is located on a kind of plateau, with the terrain sloping slightly towards the North and West. Although there appear to be some differences in site quality within the experimental area (see below in the description of the incubation experiments, and Tamm et al., in prep.), our studies of

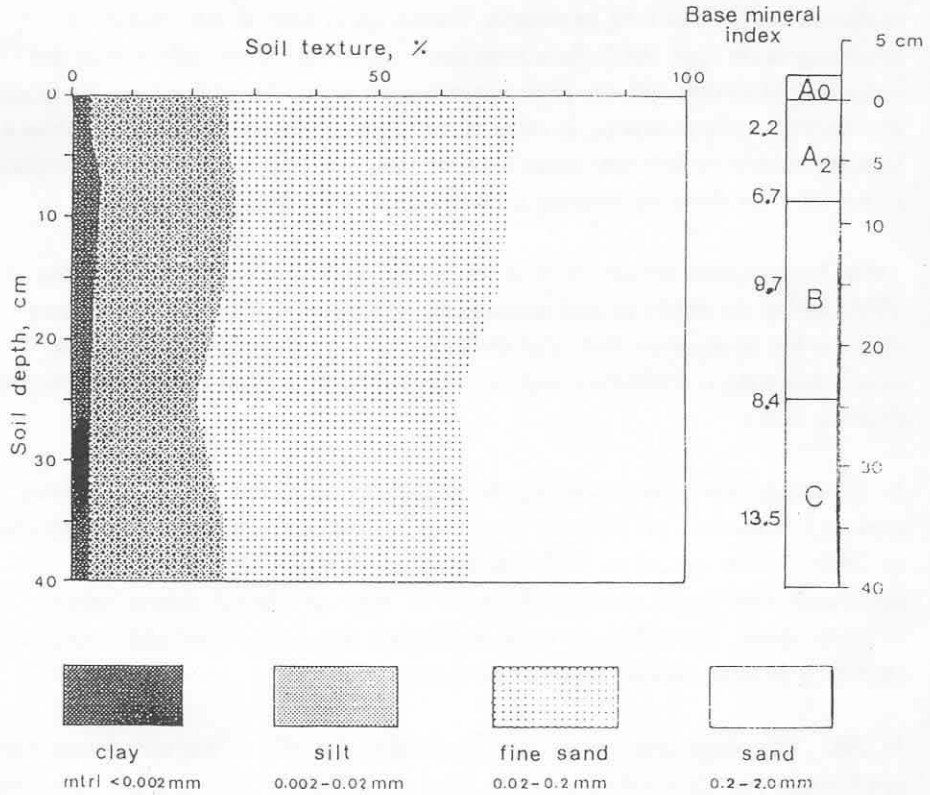


Fig.3.1. Variation of soil texture and base mineral index with depth in one typical profile at **Norrliden** (control plot No. 16, soil material < 2 mm). Soil horizons to the right. From Hallbäcken & Popovic, 1985.

soil characteristics have not revealed any large differences in stoniness (Appendix, Table 8.1, middle part) or depth of the bleached horizon (Table 8.1., lower part). Both these properties are - other things being equal - considered as indicators for differences in site productivity. Soil texture has not been studied as systematically as the properties in Table 8.1., but Fig.3.1 provides an example of a profile with small textural differences with depth in the uppermost 40 cm of the mineral soil. Two other profiles offer a similar picture. The texture of the accumulation horizon (B) has been studied in 11 profiles, distributed over the three experimental blocks of Experiment E57, and the results, reproduced in Fig.3.2, indicate a remarkable homogeneity in texture in these profiles.

Several soil samplings have been made in Experiment E57 on different occasions, comprising the whole experiment, or certain treatments or plots only. Most samplings have dealt with the humus layer only, and have been made using soil augers in order to disturb the plots as little as possible. Samplings of mineral soil, except by small augers (in June 1985), have been restricted to the shelter belts outside the measuring plots (but with the same treatments as these). Samplings intended to give representative plot estimates, as those made in June 1985 and reported in Tables 8.2 to 8.10, have been well distributed over the sampling area, usually by sampling at preset intervals along a measuring tape stretched along the plot diagonals.

Table 3.1 compares the pH levels of the humus layer from an autumn sampling in 1974, during the period of acid application, with those in June 1985, nine years after the last application. For 12 of the plots there are also pH levels available from a sampling in 1980 for a study of liming effects on forest soils (Hallbäcken & Popovic 1985).

In 1974 there was a statistically significant decrease in humus pH with increasing acid application (0.1 pH units per step acid) in treatments with NPK, and also when all 24 plots were compared, while the decrease in pH was not statistically significant when the 12 unfertilised plots were taken as a group, due to some outlying values. The difference between fertilised and nonfertilised plots was small (fertilised plots on average 0.08 pH units higher).

In 1985, nine years after the last acid application, but with annual ammonium nitrate applications and PK applications every third year (Table 2.2), humus pH values were generally higher than in 1974, independently of treatment, with limed + fertilised plots as the exception. Yet it may be difficult to compare pH levels between different samplings as there is a certain seasonal variation and possibilities of a between-year variation. Even if the difference found here between 1974 and 1985 is

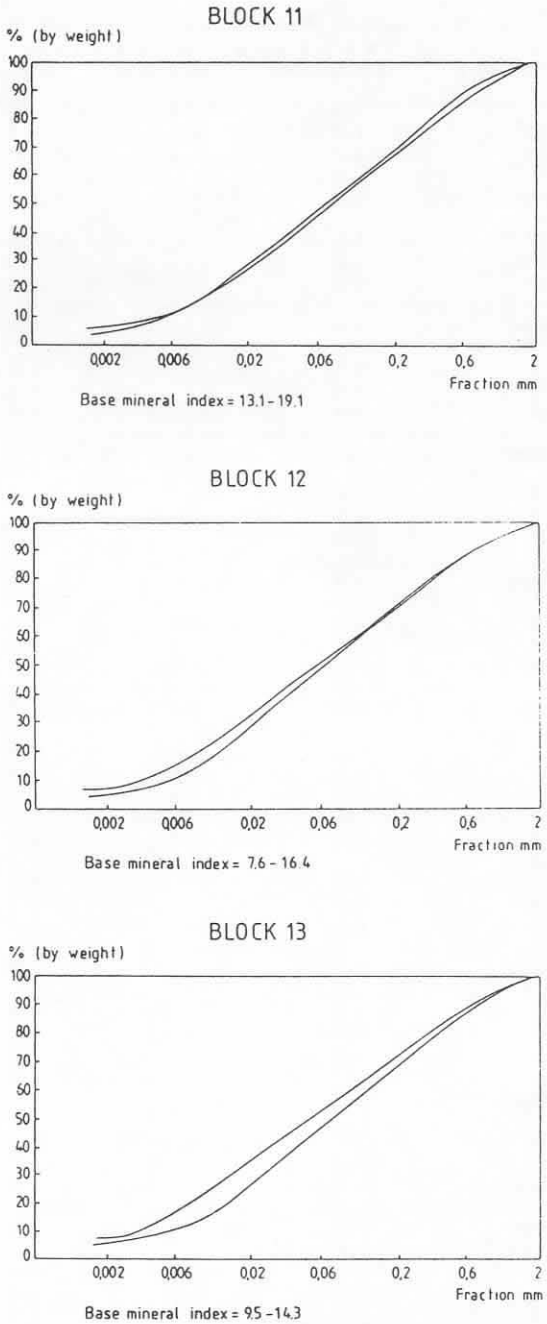


Fig.3.2. Soil texture of B horizon samples from Experiment **E 57** (Blocks No. 11, 12 and 13, 3-5 samples from each). The curves show the accumulated amounts of particles below the diameters noted on the X-axis in the material < 2 mm. Only the highest and lowest curve from each block is shown. The range of the base mineral index in each block is given below each diagram.

Treatment	Plot,No	Sampling occasion 1974,October	1980,July	1985,June
Control	6	3.8	4.6	4.2
	16	4.7	4.7	4.3
	23	4.2	4.4	4.3
	mean	4.2	4.6	4.3
Acid 1	1	3.5	-	4.1
	20	4.0	-	4.2
	25	3.9	-	4.4
	mean	3.8	-	4.2
Acid 2	3	3.5	-	4.2
	13	3.8	-	4.2
	22	3.9	-	4.2
	mean	3.7	-	4.2
Acid 3	5	3.6	-	4.0
	19	4.3	-	4.5
	27	3.8	-	4.1
	mean	3.9	-	4.2
Lime	8	6.4	6.0	6.8
	17	6.4	5.9	6.9
	30	6.8	5.9	7.0
	mean	6.5	5.9	6.9
N P K	7	4.0	4.4	4.6
	15	4.2	4.6	4.7
	29	4.2	4.6	4.6
	mean	4.1	4.5	4.6
" + Ac 1	10	4.2	-	4.6
	18	4.1	-	4.3
	21	4.1	-	4.7
	mean	4.1	-	4.5
" + Ac 2	4	3.7	-	4.6
	12	4.1	-	4.6
	24	4.0	-	4.5
	mean	3.9	-	4.6
" + Ac 3	2	3.6	-	4.5
	11	3.9	-	4.5
	26	4.0	-	4.4
	mean	3.8	-	4.5
" + Lime	9	6.6	6.6	5.9
	14	6.7	6.2	6.0
	28	6.6	6.2	6.3
	mean	6.6	6.3	6.1

Table 3.1. Expt **E57**, Norrliden. measurements of **pH** in humus layer (in water suspension) from differently treated plots, at samplings in October 1974, July 1980 and June 1985.

larger than the seasonal variation found by Hesselman (1937, cf. also Tamm & Hallbäcken 1988) in an area not far from Norrliden and with similar soil and vegetation, it is difficult to draw reliable conclusions from differences between samplings in different years. We will therefore proceed to the results of the 1985 samplings, reported in Tables 3.2 and 3.3 and illustrated in Figures 3.3 to 3.9. More detailed data are given in the Appendix (Tables 8.2 - 8.10).

The soil sampling in 1985 comprised the upper mineral soil, divided into three layers (0 - 5 cm, 5 - 10 cm, and 10 - 20 cm) in addition to the humus layer. The results of the chemical analyses expressed as concentrations have been tested in a statistical analysis (ANOVA), Table 3.2. The table also gives numerical values for the differences with or without the treatment (for acid treatments average of Acid 1 - 3 against no acid).

It is evident from Table 3.2 (supplemented with the more detailed information in the Appendix, Tables 8.2 - 8.6) that there are statistically significant differences in pH, V%, exchangeable Ca, Mg and K in most horizons for the comparison between fertilised and unfertilised plots. In the humus layer the fertilisation has decreased acidity, measured as pH or V%, but increased it in the mineral soil. Titratable acidity (TA) has also increased in deeper layers of fertilised plots, while the effect on the humus layer and the horizon 0 - 5 cm is non-significant in this parameter. Cation exchange capacity is increased in the mineral soil but not in the humus layer (non-significant negative difference).

The acid treatments have significantly decreased pH, V%, total exchangeable base cations (TEB), Ca and Mg in the mineral soil. In the humus layer all changes go in the same direction as in the mineral soil except for Mg, but none of the effects is statistically significant. There is no clear indication that the acid treatment has affected the carbon content of any horizon, while there is an indication that the already low total nitrogen concentration might have decreased further in lower mineral horizons. The interaction Acid x NPK is significant in one single case (negative interaction for Mg in 10-20 cm mineral soil).

Table 3.2. Expt E57, Norrliden. Results of ANOVA tests of treatment effects on chemical concentration variables in soil from differently treated plots. The degrees of freedom for error amount to 16 in the test of Acid and NPK effects and 8 in the test of Lime and NPK effects. Asterisks (one, two or three) denote the P levels (0.05, 0.01 and 0.001) in the ANOVA test. For main effects the sign and the numerical difference are presented for situations with and without treatment (for Acid between an average of Acid 1-3 compared with Acid 0). For interactions, only the sign and the asterisks for significance, if any, are presented. Sampling in June 1985. For dimensions of the parameters, see Tables 8.2 - 8.6.

Treatment effect	DF	Variables pH	H	K	Na	Mg	Ca	TEB	CEC	V%	Al	C	N	C/N
Humus														
NPK	1	+0.35***	-44.0	-0.12	-0.12	-3.85**	+18.7	+14.0	-29.5	+5.7**	-48.8**	+2.50	+0.13	-1.9
Acid	3	-0.10	+60.5	+0.70	+0.01	+0.35	-0.7	+0.3	+60.9	-3.0	+21.7	+1.50	+0.01	+0.7
AcidxNPK	3	+	-	+	-	-	+	+	-	+	-	+	+	-
Lime	1	+2.04***	-241***	+1.64	+0.08	+1.98	+440***	+444***	+203**	+67.8***	-67.2***	-9.99***	-0.23*	-1.4
LimexNPK	1	- ***	+ *	+	0	-	-	-	-	- **	+	+	+	-
0–5 cm, mineral soil														
NPK	1	-0.11*	+4.2	+1.63***	-0.04	-0.11	+1.8**	+3.2***	+7.4*	+3.2*	-54.3**	+0.08	+0.01	-1.4
Acid	3	-0.11*	-1.1	+0.11	-0.03	-0.25*	-2.9***	-3.1***	-4.1	-4.3**	+30.9	0.00	0.00	-1.4
AcidxNPK	3	-	+	+	-	-	+	+	+	+	-	+	+	-
Lime	1	+0.94***	-21.7**	-0.21	-0.05	+0.34	+34.3***	+34.4***	+12.7	+45.2***	-177.7***	+0.11	+0.004	+0.6
LimexNPK	1	- **	+	+	+	-	-	-	+	- *	+	+	+	- *
5–10 cm, mineral soil														
NPK	1	-0.42***	+11.0***	+1.11***	-0.05	-0.22***	-0.84	0.00	+11.0***	-2.6	+52.5**	0.00	0.00	-1.5
Acid	3	-0.19***	+0.8	+0.08	-0.05	-0.20*	-2.2**	-2.4*	-1.6	-4.4*	+32.8	-0.07	-0.01*	+2.6
AcidxNPK	3	-	+	+	-	-	-	+	+	-	+	-	0	-
Lime	1	+0.39***	-7.8*	+0.03	-0.03	-0.01	+6.7***	+6.7***	-1.1	+14.0***	-69.4***	-0.10	+0.006	-0.02
LimexNPK	1	-	-	+	-	-	-	-	+	-	+	+	+	-
10–20 cm, mineral soil														
NPK	1	-0.50***	+5.3*	+0.66***	-0.04	-0.14***	-0.8***	-0.3	+5.0	-3.6*	+30.7***	+0.11*	+0.006*	-0.8
Acid	3	-0.21*	+4.6*	-0.03	-0.04	-0.15***	-0.9*	-1.0*	-3.6*	-5.2**	+12.2	-0.06	-0.005*	+1.4
AcidxNPK	3	-	+	+	-	- **	-	-	+	-	+	+	+	-
Lime	1	+0.25*	-5.2*	-0.01	-0.02	-0.07	+2.1**	+2.0**	-3.3	+10.8***	-11.2	-0.13	-0.005	-0.1
LimexNPK	1	-	+	+	-	- *	+	+	+	-	-	+	+	-

The most consistent treatment effects are those due to liming, which has decreased acidity in all soil horizons, increased the concentrations of exchangeable calcium and decreased aluminium concentrations, as expected from earlier studies (e.g. Hallbäcken & Popovic, 1985). It has also decreased the humus layer carbon and nitrogen concentrations. Some of the first order interactions Lime x NPK are statistically significant, for pH and V% in the humus layer and uppermost mineral soil (negative sign) and for total acidity in the humus layer (positive sign).

The statistical analyses summarised in Table 3.2 do not fully utilise the information built into the experimental design, as the comparisons concern Acid versus Control, while there are in fact four different levels of Acid in the experiment. Figs.3.3 - 3.6 illustrate the regressions of pH, V%, Ca-exch. and Mg-exch. on Acid level, with the significance of the correlation expressed by asterisks and the proportion of the variation explained by the regression given as the R^2 value.

For mineral soil, plots without fertilisation, it can be seen in Figs. 3.3 to 3.6 that the regression lines (with increasing amounts of added acid) explain between one-third and more than two-thirds of the total variation in the four properties, while there is no significant effect in the humus layer. On the fertilised plots, most mineral soil regressions are also significant, although the explained part of the total variation is usually lower. No humus layer regressions are statistically significant, but the levels of the lines are somewhat higher for fertilised humus layers than for unfertilised ones as regards pH, V%, and Ca, as indicated earlier.

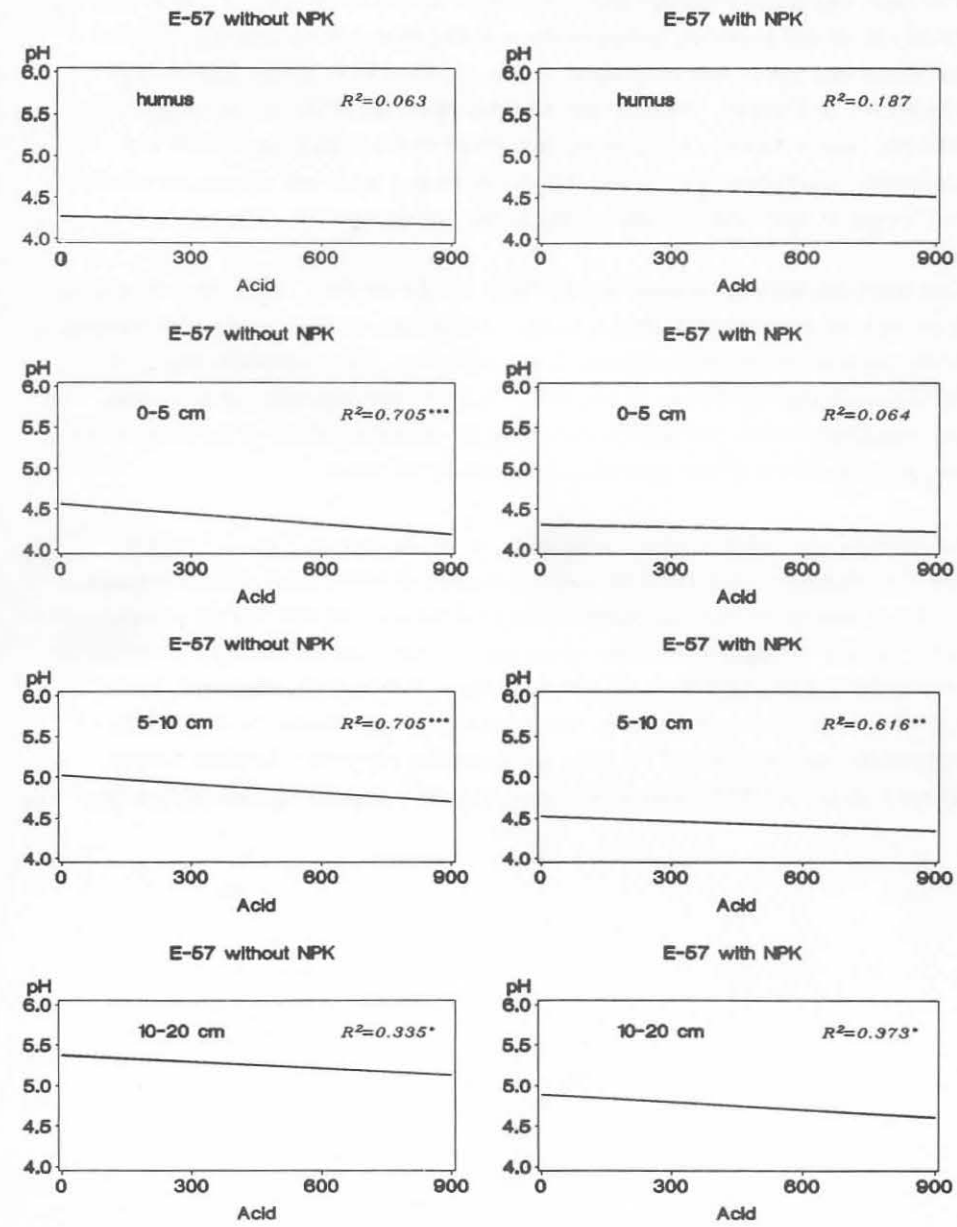


Fig. 3.3. Soil pH in different horizons as a function of acid application in Experiment E 57, based upon the same data as Table 3.3. "Degree of Explanation" given as R^2 values, and significance levels with asterisks. Left: without NPK, right with NPK. Sampling in 1985.

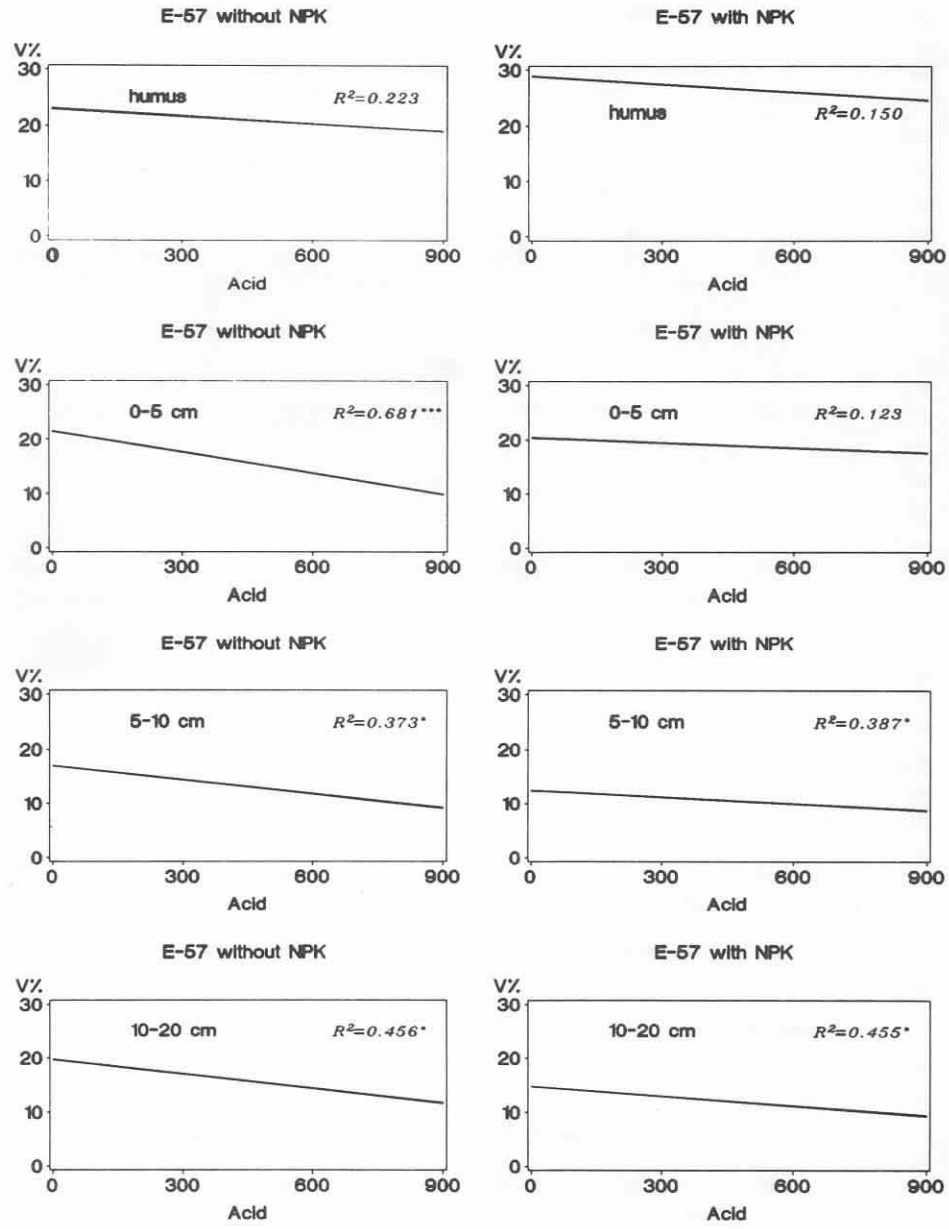


Fig. 3.4. "Base saturation" (V%) in different horizons as a function of acid application in Experiment E 57. See further Fig. 3.3.

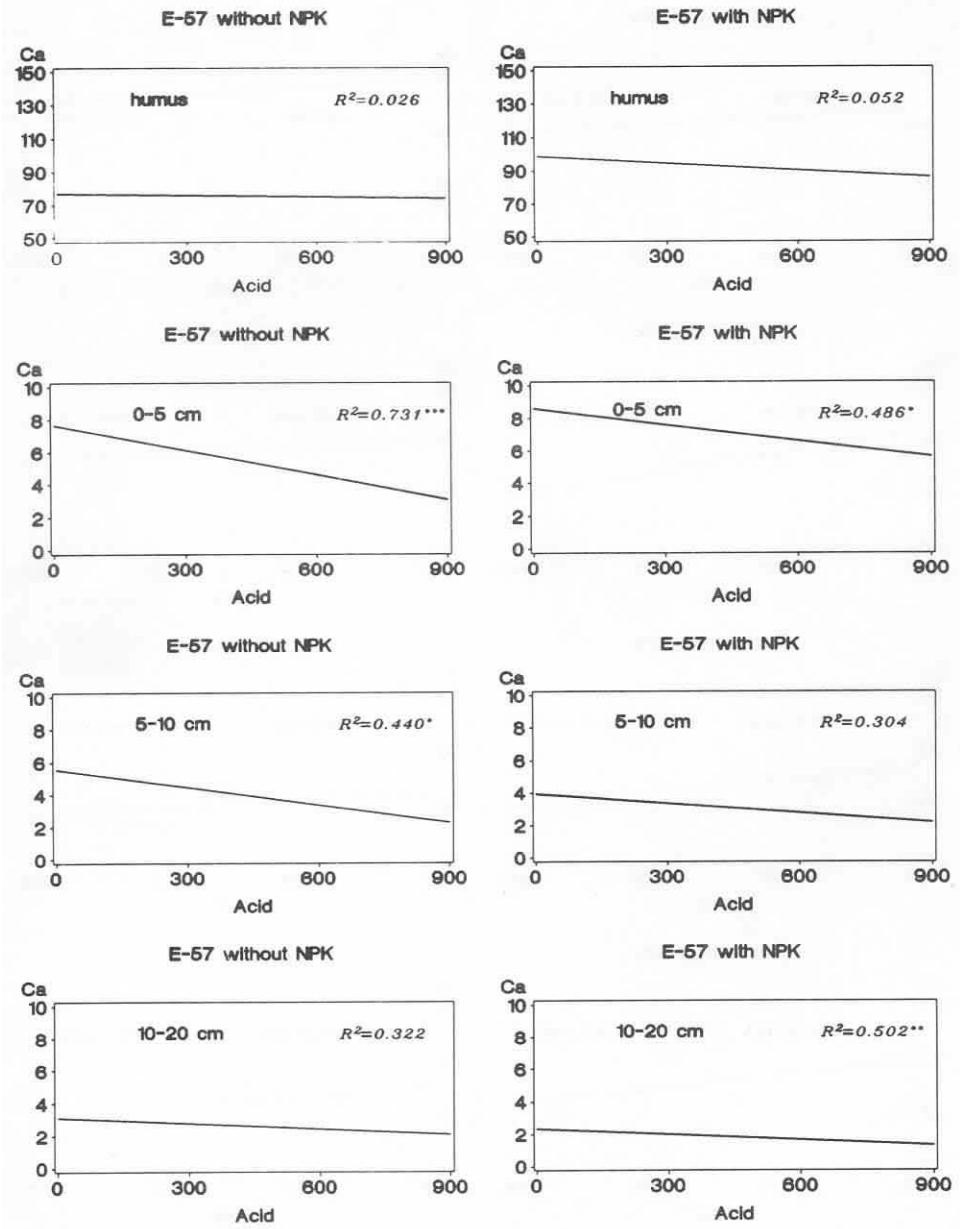


Fig. 3.5. Calcium concentration (μeq/g D.M.) in different horizons as a function of acid application in Experiment E 57. See further Fig. 3.3.

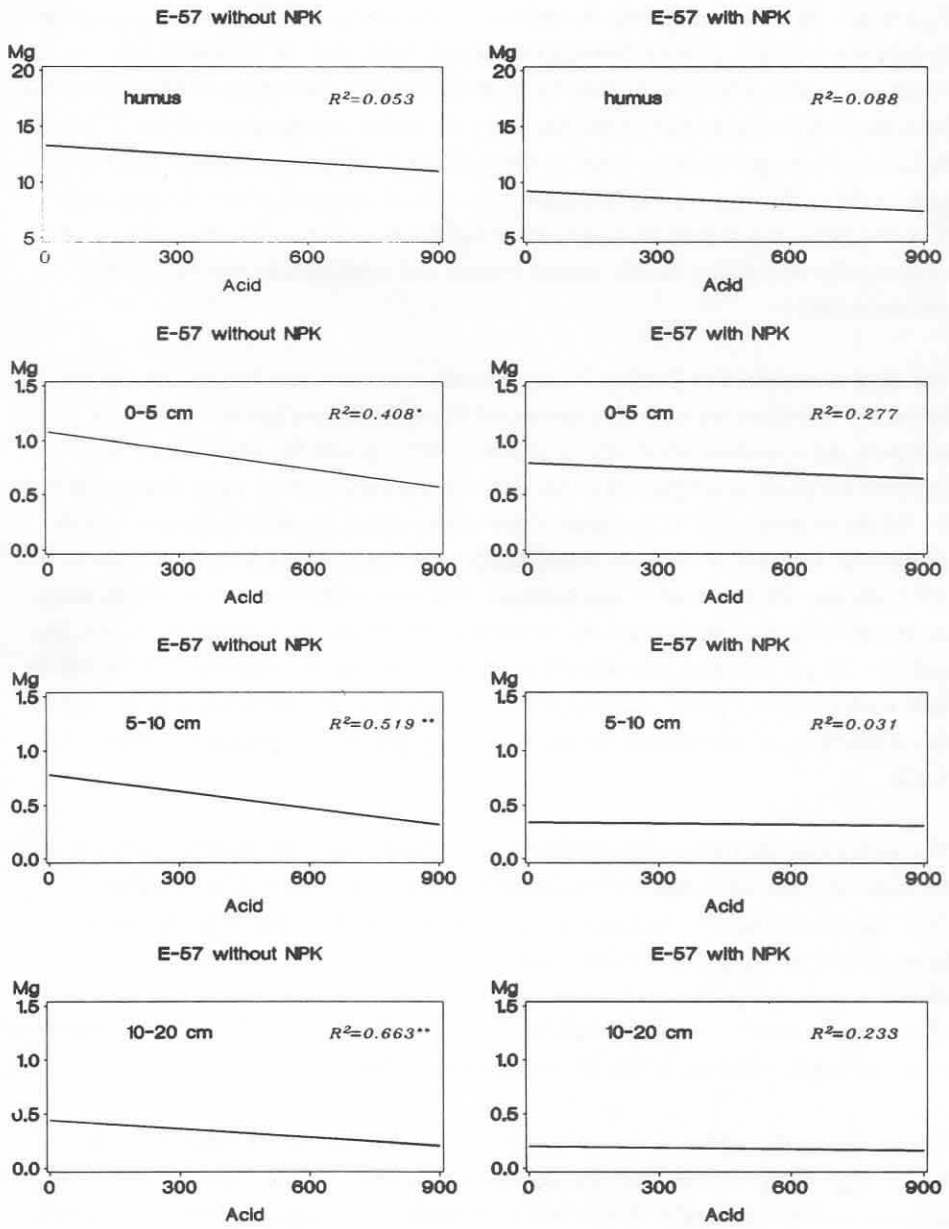


Fig. 3.6. Magnesium concentration (μeq/g D.M.) in different horizons as a function of acid application in Experiment E 57. See further Fig. 3.3.

Figure 3.7. gives an illustrative comparison of the effects on pH and base saturation in different horizons of NPK fertilisation on one hand, and the strongest acid treatment on the other. Yet it must be remembered that the supply of nitrate ions has been much higher than that of sulphate over the entire experimental period if counted as moles of charge. If, then, some of the ammonium ions nitrify, which was not the case in the early phase of the Norrliden experiments (Popovic 1977) but may have occurred later, this means an acidification additional to that caused by leaching of cations with percolating mobile anions (nitrate and sulphate), as will be further discussed below.

The data summarised in Table 3.2 only concern concentration data for the various horizons. Therefore we have also calculated the amounts per hectare of various elements, an operation which also makes it possible to add the amounts for the different horizons to a figure valid for much of the main rooting zone (humus layer + 0 - 20 cm mineral soil). In the case of the humus layer, the data necessary for this calculation were taken from the actual sample data (auger samples with known surface area) whereas for the mineral soil horizons they were taken from the stoniness index as described in Section 2 (Fig.2.5), where also the weight of horizons 0 - 5, 5 - 10, and 10 - 20 cm had been determined separately (without any significant difference in bulk density). The figures obtained for the humus layer on one hand, and the upper two decimetres of mineral soil on the other are given in the Appendix (Tables 8.8 to 8.10).

The area based data have been subjected to a similar statistical analysis (ANOVA) as the concentration data, and the results are presented in Table 3.3. It is evident from the results that the fertilisation has increased the amount of organic matter (carbon) and nitrogen in the humus layer, but not particularly affected the total amounts of exchangeable protons (H) in the humus layer, while there seems to be an effect deeper down. Liming has had the expected effects on H, Ca-exch. and aluminium in all horizons, while the effect on magnesium is lower.

Only a few of the effects of the acid treatments are significant in Table 3.3. (Ca exch., Mg exch., in some cases H and extractable aluminium). None of the humus layer differences between Acid and No Acid is significant. However, as mentioned earlier, the analysis of variance does not use all the available information, viz. that the acid treatments form a series of increasing applications. We have therefore prepared diagrams analogous to Figs.3.3 - 3.6., for Ca-exch. (Fig.3.8) and Mg-exch. (Fig.3.9).

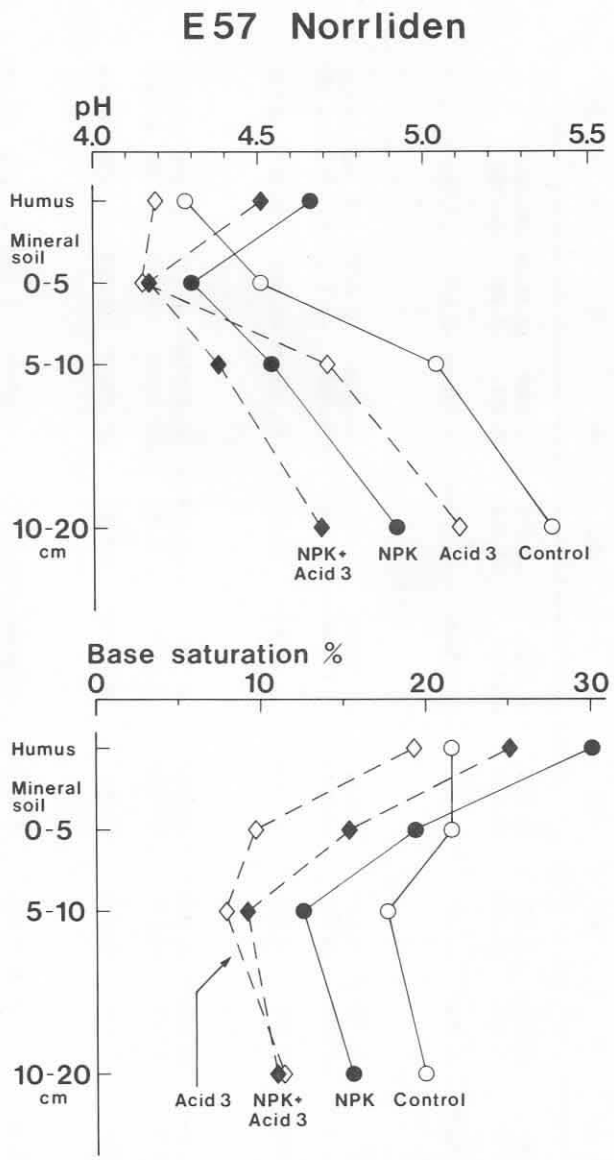


Fig. 3.7. Soil pH in water suspension (A) and V% at pH 7 (B) in different horizons in four of the treatments in Experiment E 57, in June 1985. Data from Table 8.2. Sampling in 1985.

Table 3.3. Expt E57, Norrliden. Results of ANOVA tests of treatment effects on chemical variables in amounts per hectare. The degrees of freedom for error amount to 16 in the test of Acid and NPK effects and 8 in the test of Lime and NPK effects. Asterisks (one, two or three) denote the P levels (0.05, 0.01 and 0.001) in the ANOVA test. For main effects the sign and the numerical difference are presented for situations with and without treatment (for Acid between an average of Acid 1-3 compared with Acid 0). For interactions, only the sign and the asterisks for significance, if any, are presented. Sampling in June 1985. For dimensions of the parameters, see Tables 8.8-8.10.

Treatment effect	DF	Variables H	K	Na	Mg	Ca	CEC	Al	C	N	SO_4
Humus											
NPK	1	-0.004	+0.030	-0.001	-0.072	+0.898*	+0.849	-1.209*	+2.714**	+98.041**	
Acid	3	+0.976	+0.047	+0.003	+0.052	+0.271	+3.603	+0.951	+2.289	+54.760	
AcidxNPK	3	-	+	-	-	+	+	-	+	+	
Lime	1	-6.048***	+0.096*	+0.078	+0.135*	+15.173***	+9.378**	-1.701***	-0.499	+1.534	
LimexNPK	1	+	+	-	-	-	-	+	+	+	
0–5 cm, mineral soil											
NPK	1	+2.233	+0.705***	-0.017	-0.034	+0.795***	+3.683*	-94.554*	+0.442	+29.142	+1.157
Acid	3	-0.222	+0.052	-0.012	-0.101*	-1.153***	-1.444	+14.468	+0.132	+13.561	+2.089
AcidxNPK	3	+	+	-	+	+	+	-	+	+	-
Lime	1	-8.923**	-0.082	-0.191	+0.152*	+14.643***	+5.750	-73.568***	+0.585	+19.967	-2.136
LimexNPK	1	+	+	+	-	-	-	+	+	+	+
5–10 cm, mineral soil											
NPK	1	+5.100***	+0.484***	-0.020	-0.091**	-0.335	+5.125***	-26.612***	+0.151	+17.991	+6.170
Acid	3	+0.622	+0.054	-0.019	-0.082*	-0.897*	-0.361	+15.333*	-0.295	-31.550	+4.380
AcidxNPK	3	+	+	-	- *	-	+	+	-	+	+
Lime	1	-2.934*	+0.034	-0.100	+0.003	+2.842***	-0.067	-27.396***	+1.269	-21.533	-6.160
LimexNPK	1	+	+	-	-	-	+	+	-	+	+
10–20 cm, mineral soil											
NPK	1	+4.959*	+0.572***	-0.037	-0.119***	-0.610**	+4.775*	-3.482***	+1.198*	+61.192*	+72.190
Acid	3	+4.294*	+0.015	+0.289	-0.102***	-0.720**	+3.506*	+11.681	-0.391	-38.505	+54.530
AcidxNPK	3	+	+	-	- **	-	+	+	+	+	+
Lime	1	-3.967**	+0.014	-0.307	+0.046	+1.823**	-2.167	-8.039	-0.944	-36.200	+9.900
LimexNPK	1	+	+	-	-	+	+	-	+	+	+

However, before these diagrams can be interpreted we must ascertain that possible regressions cannot wholly or partly be explained by systematic differences in weights or total cation exchange capacity (CEC) between treatments (which is a theoretical possibility, though not very likely). A check on possible relations between horizon weights and CEC on one hand, and the acid treatments on the other, has been made in the Appendix, Figs. 8.1 and 8.2. This analysis indicates no systematic trends of horizon weights with increasing acid application. In Table 3.3 there is one case of "significant" increase in CEC in 10 - 20 cm mineral soil, but the sign of the coefficient changes irregularly between horizons and only two per cent of of the variation is explained by the regression in Fig.8.2. Thus, rejection of the null hypothesis of no relation might well mean a "type I error" in the statistical sense, where a randomly occurring aberrant value is taken as indicating a true difference.

We can now conclude that the mineral soil horizons have lost exchangeable calcium and magnesium with increasing acid application. For calcium, five out of six regressions are significant, with R^2 values between 0.32 and 0.58. For magnesium three out of six regressions are significant (with R^2 values 0.41 - 0.42). A rough calculation indicates that addition of 900 kg H_2SO_4 per hectare, or 1.8 mol of protons per square metre, has resulted in a loss of about 60 kg calcium per hectare from the upper mineral soil (0-20 cm), measured nine years after the end of the acid applications. This amount is approximately one-fourth of the store in these horizons on the control plots. In the case of magnesium, about half the store on control plots appears to have been lost, or 6 kg per hectare. Apparently the base cation losses as illustrated in Figs.3.8 and 3.9 only correspond to a small part of the added sulphate. Some of the added sulphate may have been retained in the vegetation or in the soil profile, presumably mostly in the B horizon. However, most of it must have been leached out of the upper profile together with protons or aluminium ions.

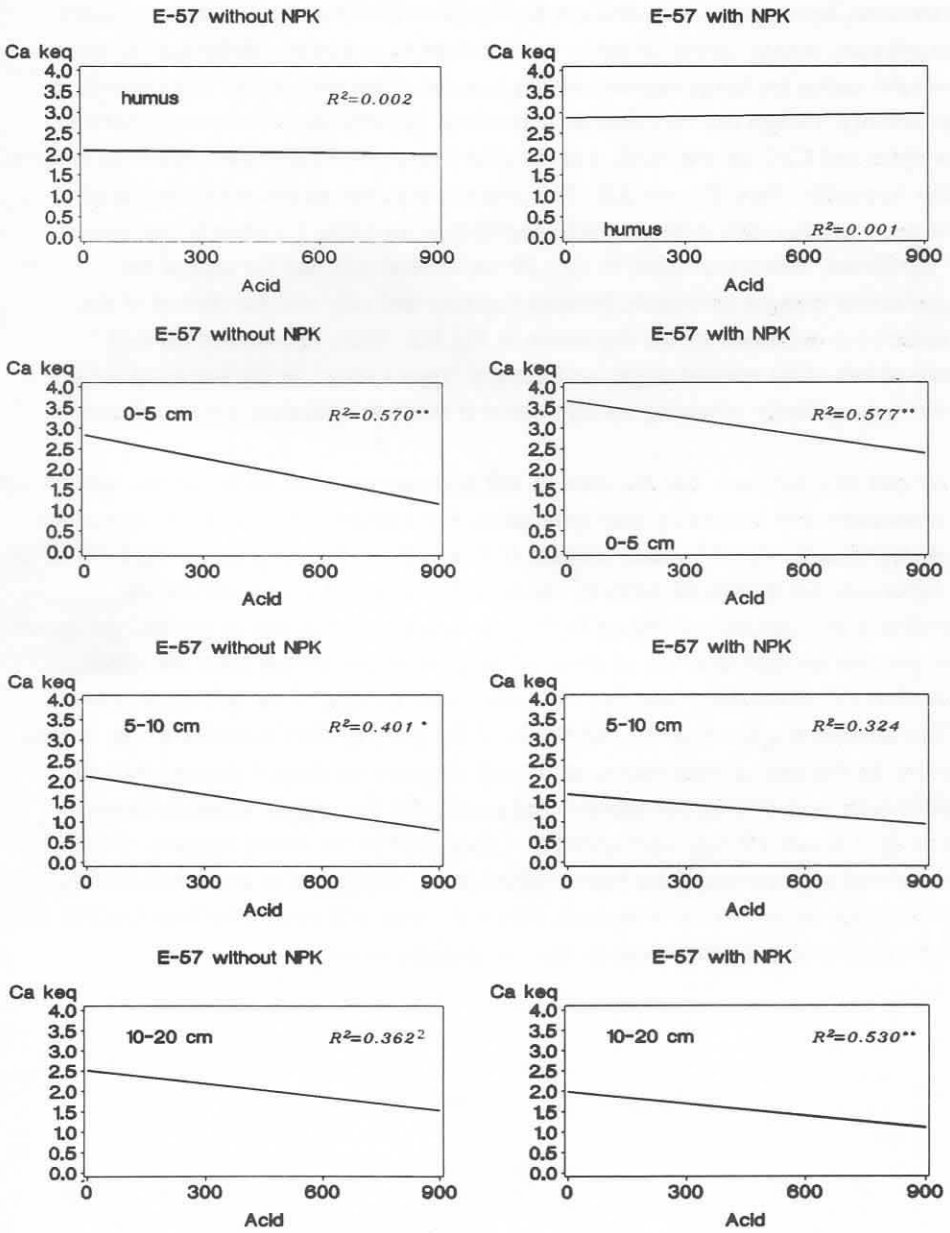


Fig. 3.8. Amounts of exchangeable calcium (keq per ha) in the humus layer and mineral soil (0-5, 5-10, and 10-20 cm) as a function of acid application in Experiment E 57.

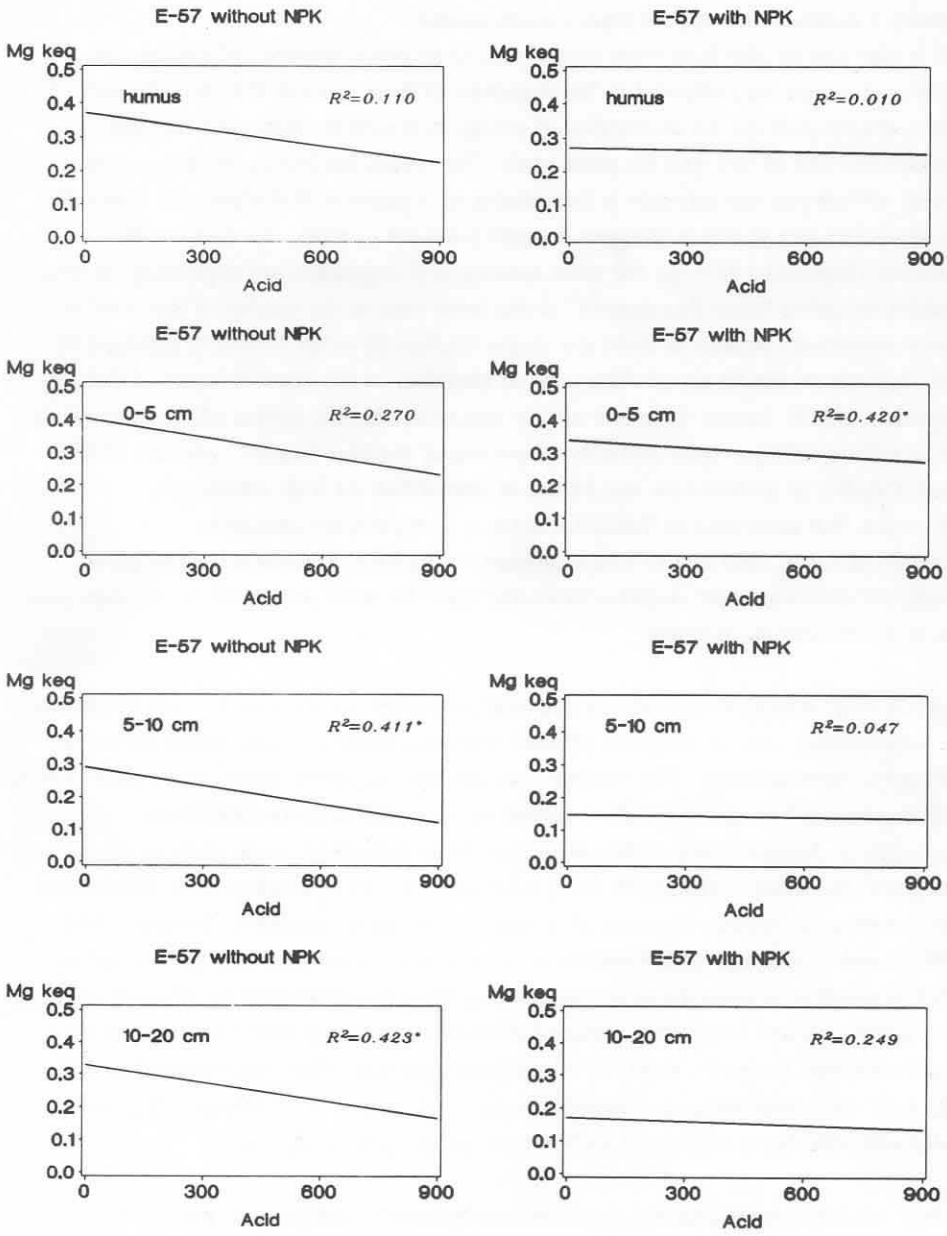


Fig. 3.9. Amounts of exchangeable magnesium (keq per ha) in the humus layer and mineral soil(0-5, 5-10, and 10-20cm) as a function of acid application in Experiment E 57.

Nitrogen mineralisation and soil organic matter turnover.

It is well-known that both total concentrations and total amounts of carbon and nitrogen in soil, as presented in the Appendix (Tables 8.6 and 8.8) provide very little information on the availability of energy-rich carbon compounds for soil organisms and of nitrogen for plant roots. The reason for this is, of course, that most soil carbon and nitrogen is unavailable to organisms. For plants the important thing is the rate at which nitrogen is made available to roots, the nutrient flux density (Ingestad 1982). In the same manner, soil organisms are depending on what might be called "food flux density" at the same time as the quality of that food is very important. Neither is there any single fraction of either carbon or nitrogen in the soil which can be successfully used to characterise the nutrient status of the system, even if humus form and nitrate occurrence have a certain informative value. The carbon/nitrogen ratio probably offers one of the best "static" measures of the soil's ability to mobilise (at low ratios) or immobilise (at high ratios) soil nitrogen, but according to Table 3.2 there is no significant change in carbon/nitrogen ratio due to acid treatment, or to NPK fertilisation, although all fertiliser differences are negative (lowering the C/N ratio) and three out of four acid differences are positive.

When static measurements of soil chemical properties so often have failed in attempts to characterise soils as suppliers of plant nitrogen, scientists have looked for more dynamic measurements. The nutrient flux density mentioned above is one such dynamic characteristic, but unfortunately it cannot be measured directly under field conditions. Various types of bioassays have been attempted, most often as incubation experiments where soil samples have been stored in the laboratory or in plastic bags in the field for periods of weeks or months. It has been stressed by Romell (1935, 1967) and others that such experiments do not necessarily give true rates of either decomposition or nitrogen mineralisation, as these processes may be affected already by cutting off the roots. Still, incubation experiments can provide information on a particular soil horizon's ability to decompose litter and other organic material and to mineralise nitrogen under disturbed conditions (e.g. a clear-felling). They can also tell whether a soil would form nitrate under such conditions.

As it has been suggested that a possible mechanism by which acid deposition may affect plant life is by disturbing the organic matter decomposition and the nitrogen mineralisation (Tamm, 1976), attempts have been made to study these processes on the Norrliden plots. Other studies of soil biological characteristics have also been made, which will be quoted below and in the Discussion.

The first nitrogen mineralisation study, supplemented with soil respiration data, was carried out by one of us (B.P.) in 1974, after four applications of both ammonium nitrate and sulphuric acid. The results have been published in part (Holmen et al., 1976; Popovic, 1984), so here we shall only include the main results. Fig.3.10A shows that the humus layer of unfertilised plots contains very little ammonium nitrogen and no nitrate. The fertilised plots, on the other hand, contain higher, but variable, amounts of ammonia nitrogen, and virtually no nitrate (Fig.3.10B). Apparently most of the nitrogen applied in the beginning of the growing period had already been immobilised or leached in October. Upon incubation for nine weeks (in the laboratory at 20^{o} C, Fig.3.10 C and D) practically all samples showed a marked accumulation of ammonium nitrogen. The exception is formed by some of the limed plots, where even immobilisation of nitrogen had occurred at least in two fertilised samples (and strong nitrification in the third sample). In samples without lime very little nitrate was formed and appreciable amounts were found only in one control plot (Fig.3.10D), so we cannot tell whether acidification has depressed nitrification, as has happened in other cases (Popovic, 1984).

The impression from Fig.3.10 is that while fertilisation, as expected from other experiments (Tamm et al., 1977), increases actual ammonium concentrations and also seems to increase nitrogen mineralisation upon incubation, other factors appear equally important. In Fig.3.10C, the consistently higher ammonia values, together with the higher nitrate values of limed+NPK in Fig.3.10D, in the first bar of each triplet, suggest a block difference.

Bååth et al.(1980, 1984) have demonstrated an increase in total fungal biomass in soil after experimental acidification, although the amount of active hyphae decreased. The same authors obtained increased Collembola numbers after acidification at Norrliden (1980), in contrast to Heugens et al.(1984) who found a decrease in numbers of the same groups in their acidified plots. Experimental acidification generally seems to reduce and liming seems to increase the microbial activity (measured as CO_2 evolution) in the soil (Popovic, 1984; Persson et al., 1989, and Lohm et al., 1984).

In contrast, the acidification seems to increase the mineralisation of nitrogen (Tamm et al., 1977; Popovic, 1984; Persson, 1988). A possible reason for this is that acidification reduces the availability of energy-rich substrates to the microorganisms, and also that applications of high doses of acids kill soil organisms that are mineralised by surviving organisms (Persson, 1988).

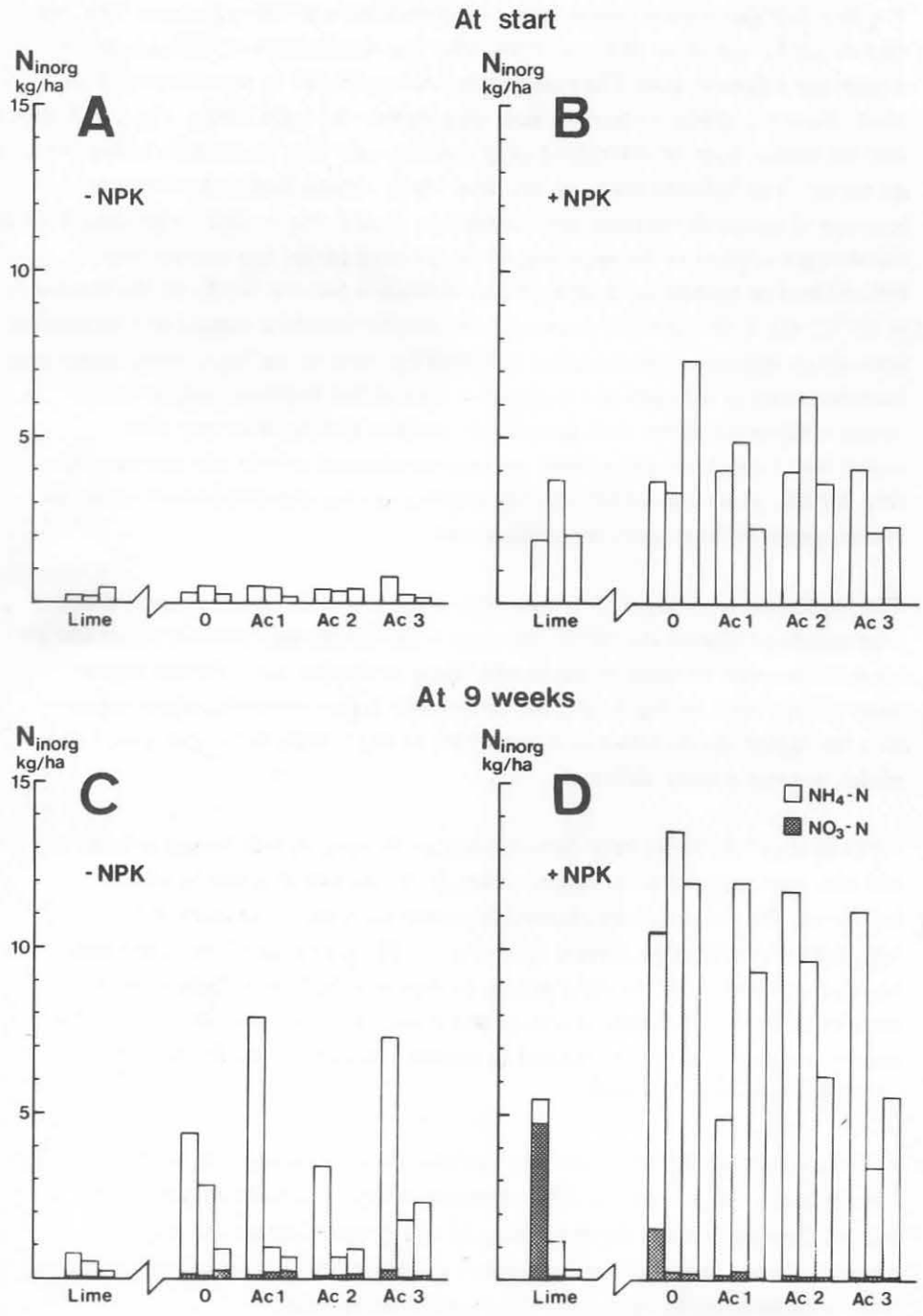


Fig. 3.10. Amounts of inorganic nitrogen at start (A and B) and after incubation during 9 weeks (C and D) in humus samples taken from experiment **E 57** in October 1974. A and C plots without NPK, B and D plots with NPK. Dark part at bottom of bars : nitrate nitrogen. Data calculated as kg nitrogen per ha.

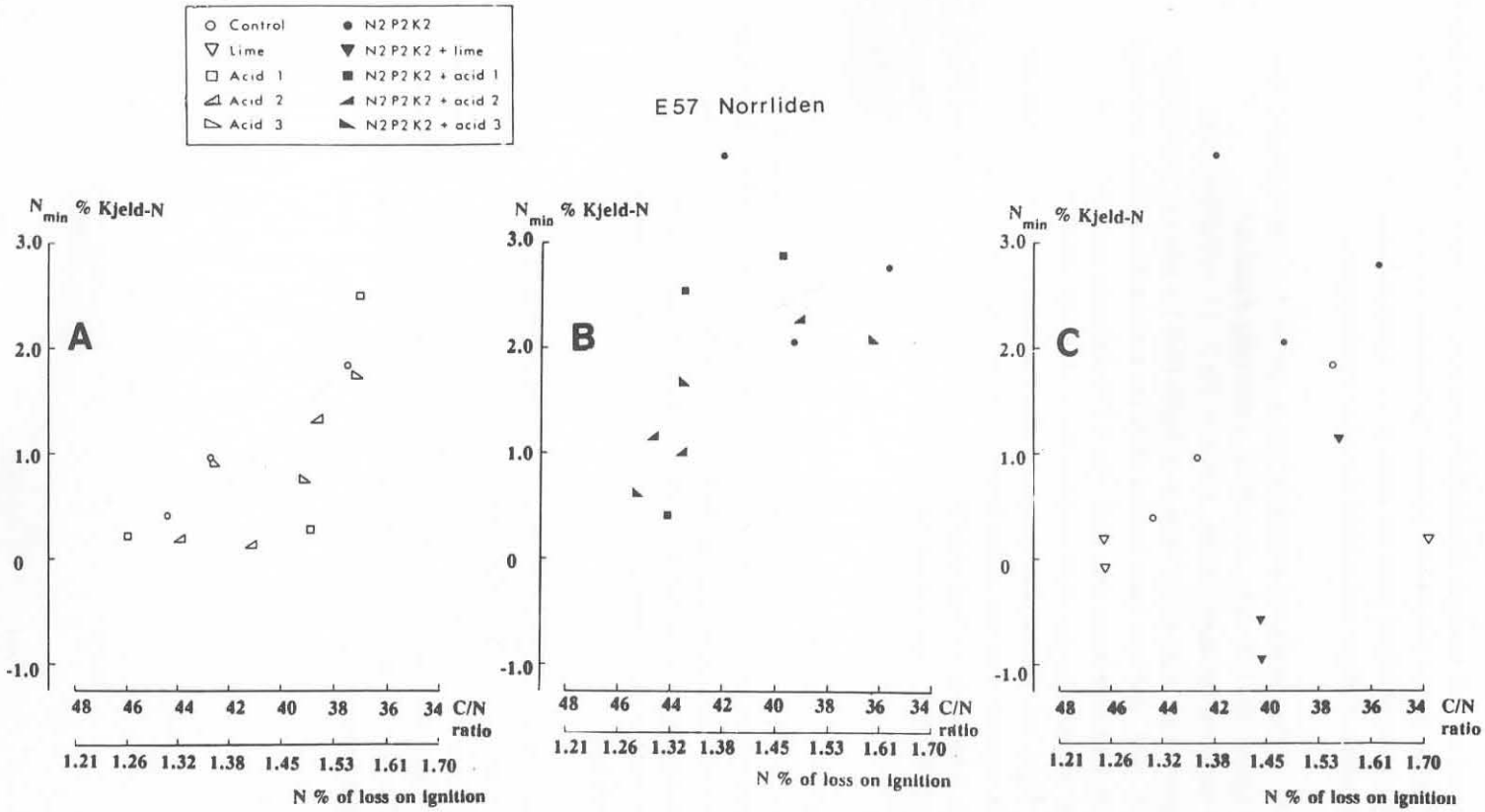


Fig. 3.11. Amounts of mineral nitrogen released in humus samples during nine weeks of incubation, expressed as per cent of total nitrogen (Kjeldahl-N) and plotted against the carbon/nitrogen ratio. **A.** Plots without NPK, with and without acid. **B.** Plots with NPK , with and without acid. **C.** Plots with lime, with and without NPK, compared with NPK only and controls. Carbon content calculated from loss on ignition.

A statistical test of the incubation data (expressed as mineralised nitrogen during 9 weeks in per cent of total nitrogen (Kjeldahl-N) was made by Popovic (1984). He found significant negative partial correlations between mineralised nitrogen and C/N ratio (unfertilised plots, on fertilised plots the relation was non-significant) and between mineralised nitrogen and acid addition (on fertilised plots).

In Fig.3.11 A - C the 9-week mineralisation values (per cent of total nitrogen) have been plotted against the C/N ratio. Even if the statistically significant relationships are those mentioned above, a look at Fig.3.11A (unfertilised and unlimed samples) may suggest that there is an upper limit for nitrogen mobilisation set by the C/N ratio, and that some but not all of the acid treatments have depressed the nitrogen mobilisation below that limit. Fig.3.11B indicates that fertilisation has raised the level of nitrogen mineralisation but is otherwise difficult to interpret. In Fig.3.11C (limed plots compared with non-limed), the three limed and fertilised plots together with one of the limed unfertilised plots show less mineralisation than expected from the C/N ratio. However, the occurrence of a single outlier (one of the NPK plots without lime) makes interpretations somewhat speculative.

Also soil respiration was studied on samples from certain treatments in the 1974 study (Popovic, 1984). There were significant treatment differences (at the 5 per cent level) between treatments (Control, Acid3, NPK, and Acid3 + NPK). Both Acid and Fertiliser decreased carbon dioxide evolution and as the deviation from the controls was larger for Acid 3 than for NPK, we may conclude that the strongest acid application decreased soil biological activity as measured in the laboratory with incubation technique.

No data of more recent origin are available on the nitrogen mobilisation within the acidification experiment at Norrliden, but Högberg et al. (1986) mention that the nitrate reductase activity in leaves of Deschampsia flexuosa was low in 1985 on limed plots of experiment E57, but elevated on ammonium nitrate plots in the adjacent experiment E55. New studies of nitrate reductase activity as well as with incubation technique are apparently called for.

3.2. Diagnostic needle analyses.

Foliar analyses provide a means to diagnose nutrient deficiencies in forest stands (Tamm, 1964; van den Driessche, 1974). Yet the method has several drawbacks. When the supply of one essential element is strongly limiting growth, other nutrients become "in excess", even if the amounts available are limited (and insufficient, if the limiting element is added). There is also a considerable between-tree variation, particularly in non-limiting elements (Tamm, 1956), not to speak of the within-tree variation and the seasonal variation. These last variations can be minimised by strict sampling procedures (position in crown, sampling season, etc.). We have tried to eliminate as much as possible of the between-tree variation by sampling the same ten trees in each plot on every occasion. Yet the conventional dormant season sampling (October-November) provides little information on the nutrient levels during the growing period. During this period, element concentrations are variable, but the physiological importance of the nutrients in the plants is highest during the growth, so that is when information would be most desirable (Waring & Youngberg, 1972).

As described in Section 2.4, pine needles were collected every year at the end of the vegetation period (late September-October) from exposed branches of the same ten dominating trees.

The results of the chemical analyses of pine needles are presented in Figs. 3.12, 3.12a and 3.13. There are some treatment effects on the needle concentrations, mainly that the addition of nitrogen and lime is well reflected in needle composition. To a lesser extent this is also true of phosphorus and potassium additions, although these effects are partly masked by the "dilution effect" on other elements by addition of the growth-limiting element nitrogen (so-called false antagonism).

In the elements nitrogen, phosphorus, and potassium there is hardly any evidence that either the acid treatments or the liming has changed the needle concentrations of the elements. Both phosphorus and potassium concentrations in the pine needles are above the deficiency range (Ingestad, 1962). In the case of nitrogen, the values on unfertilised plots are within a range typical for many pine stands where nitrogen is a growth-limiting factor (Tamm, 1956; cf. also Ingestad & Kähr, 1985). With fertilisation the level rises to about 2 per cent D.W., which is considered close to optimum. There is a between-year variation in most elements, often parallel between

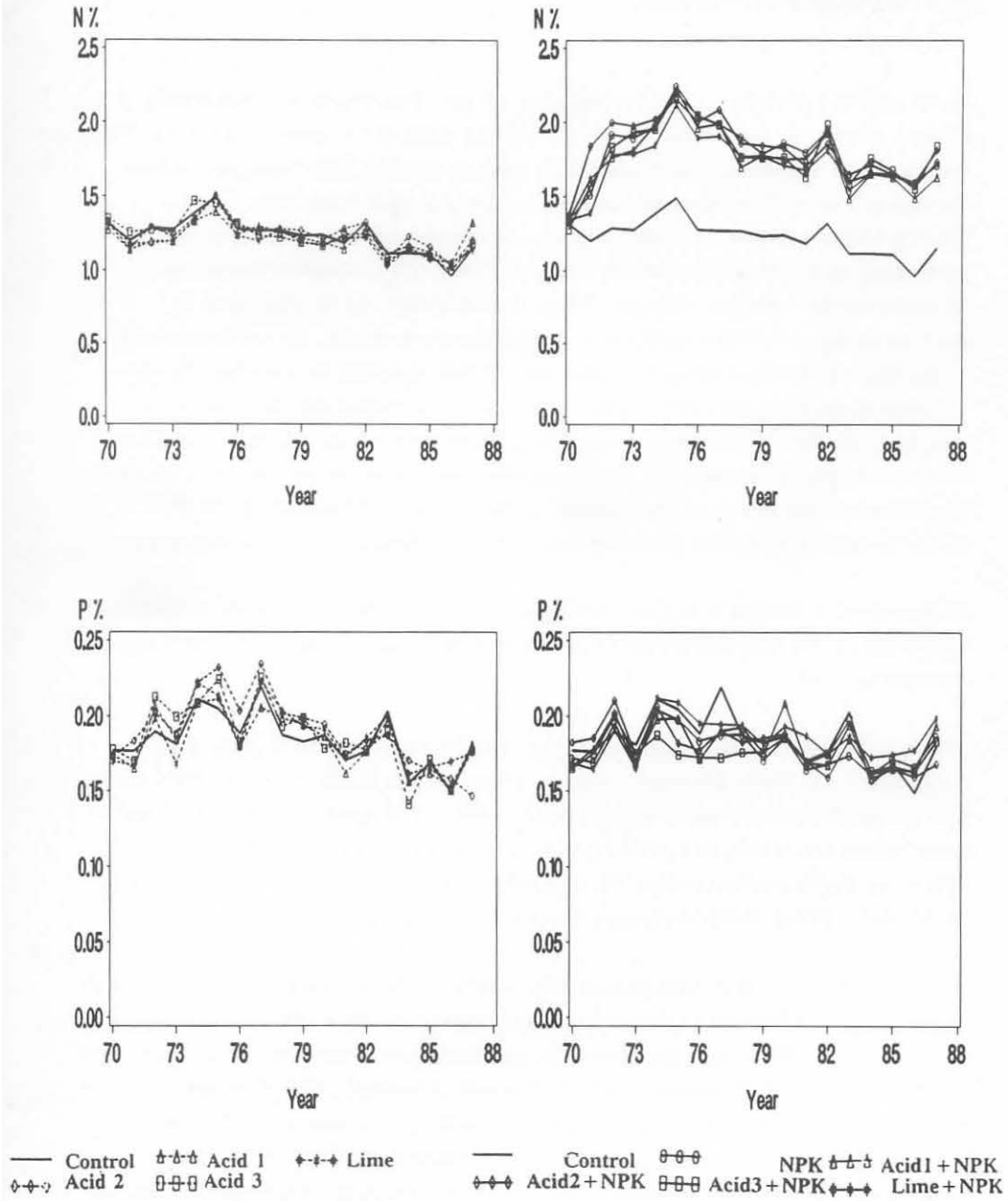


Fig. 3.12. Concentrations (per cent D.W.) of nitrogen and phosphorus in exposed current pine needles, harvested annually in October from the same ten trees in each plot of Experiment E 57. Means for three replicate plots. Left: treatments without NPK, right: treatments with NPK (plus the control, which always is a sol line without symbols).

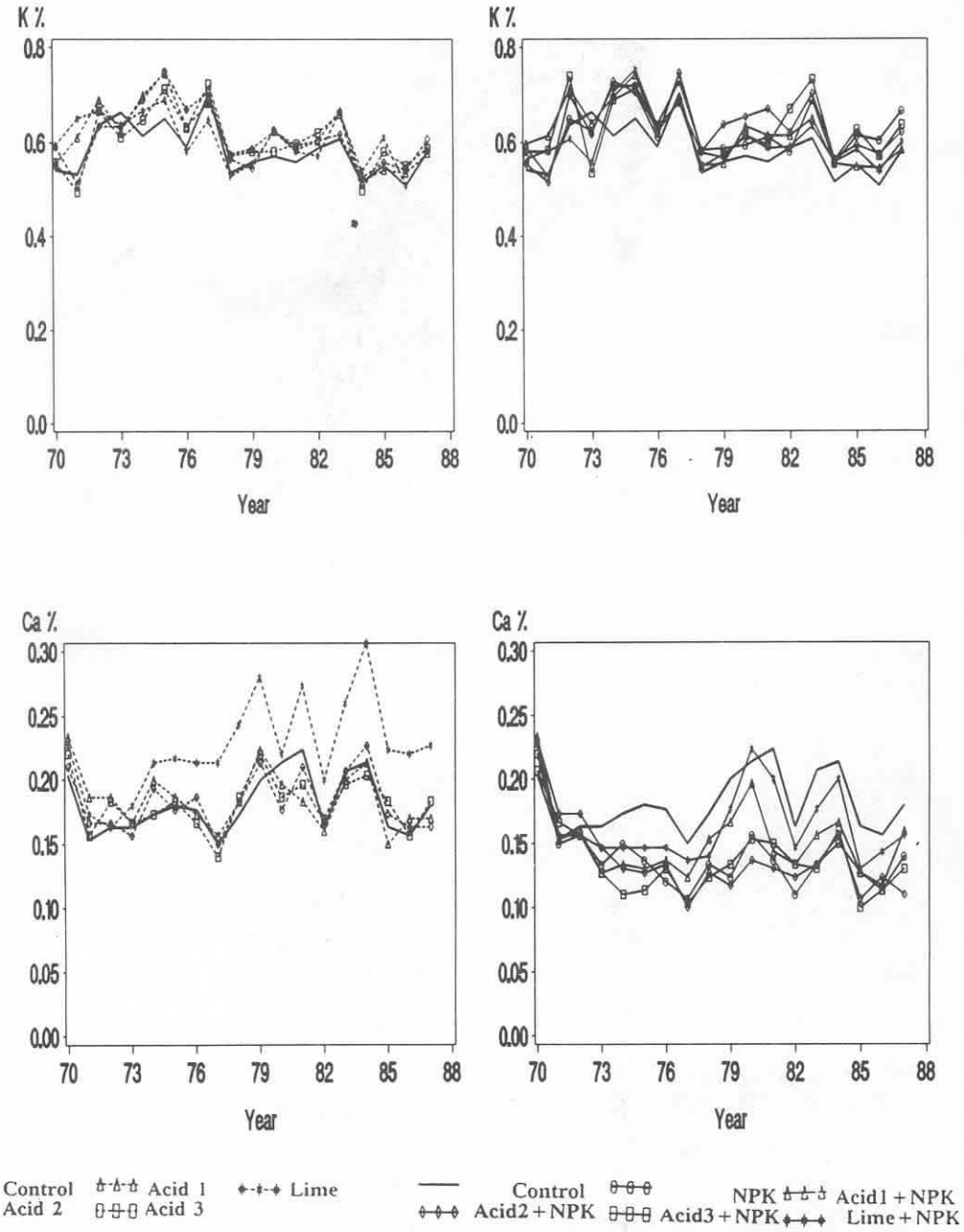


Fig. 3.12a. Concentrations (per cent D.W.) of potassium and calcium in exposed current pine needles of Experiment E 57. See further Fig. 3.12.

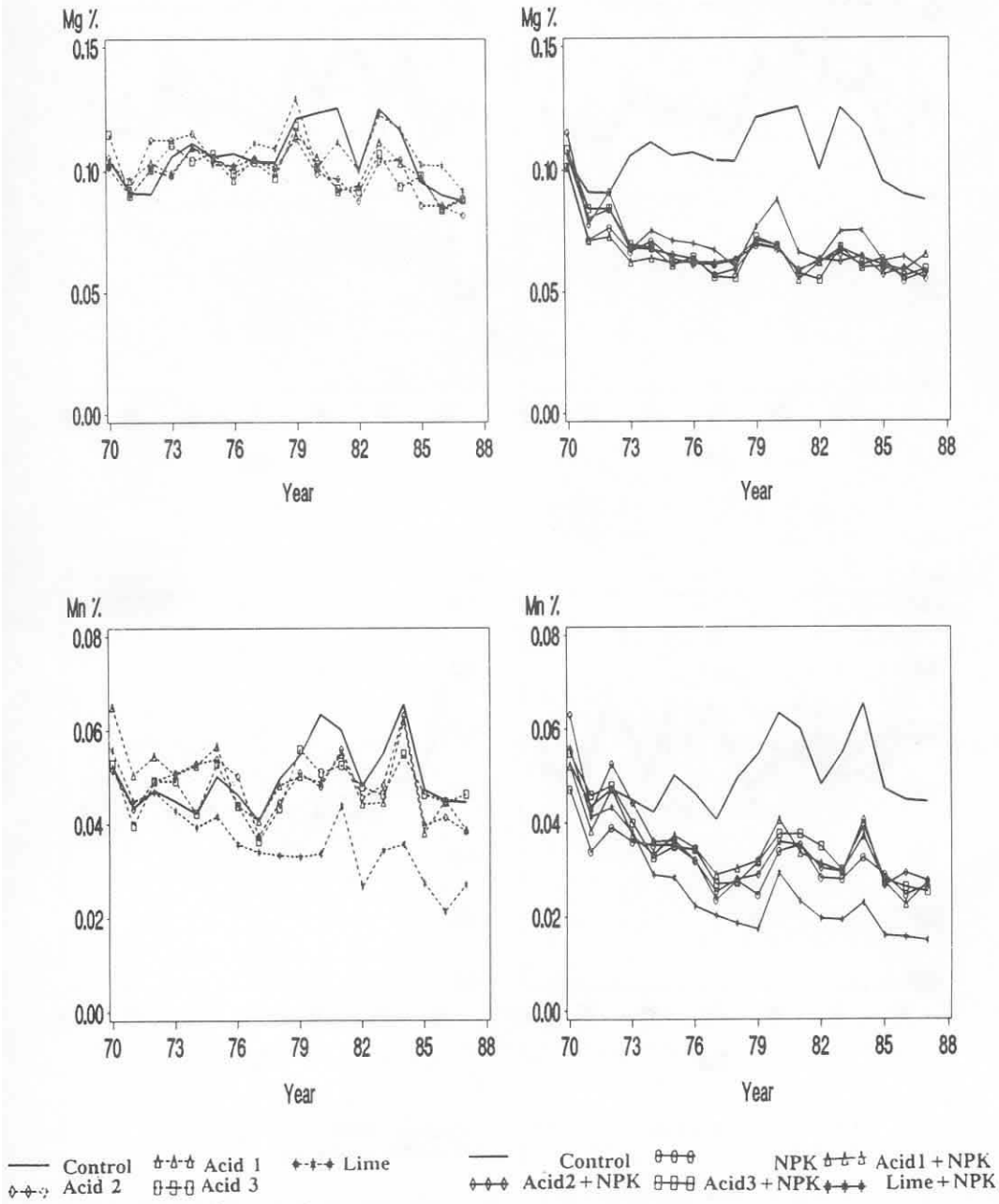


Fig. 3.13. Concentrations (per cent D.W.) of magnesium and manganese in exposed current pine needles of Experiment E 57. See further Fig. 3.12.

controls and treated plots, indicating common causes (climatic influences on nutrient uptake, on growth, or on both). In the case of phosphorus and potassium, some of the between-year variation is due to the intervals in applications (see Table 2.2).

The elements calcium, magnesium, and manganese behave differently to those discussed previously (Fig.3.12a and 3.13). It has already been mentioned that lime addition has increased calcium concentrations on unfertilised plots. On the fertilised plots the "false antagonism" with the nitrogen fertiliser is stronger than the effect of liming, which fails to maintain the same calcium levels in the needles as on the unfertilised control plots. However, unlimed fertilised plots have calcium concentrations well below the limed and fertilised ones. There is also a tendency that curves for acidified plots, which start in both diagrams (without and with NPK) slightly above the control curve, cross this curve with time and end up slightly below it.

In the case of magnesium, the "false antagonism" results in a depression of the curves for all fertilised plots to a level around 0.06 - 0.07 per cent D.W., a value where deficiency of magnesium may occur, even if visual symptoms have not yet been observed at Norrliden. In unfertilised plots there is a clear drop of the curves for acidified plots below the control during the experimental period, well in agreement with the loss of magnesium from the upper mineral soil described earlier.

Manganese concentrations in needles behave much in the same way as magnesium concentrations, with a strong "false antagonism" with nitrogen, and with a tendency towards manganese depression with acid application. Yet there is also the well-known effect of lime addition decreasing the solubility and thereby the uptake of manganese by the trees. The manganese concentrations are all above known deficiency levels (Ingestad, 1958).

In summary, it can be said that the needle analyses show but small effects of the acid treatments on needle concentrations. The effects observed, particularly the decrease in needle magnesium in trees from acidified plots, are well in line with the observed chemical changes in the soil. Among the nutrients analysed, the only ones that can be considered as growth-limiting judging from general experience of foliar diagnosis in Scots pine, are nitrogen on unfertilised plots, and possibly magnesium on fertilised plots.

3.3.Tree growth

3.3.1 Treatment responses measured as changes in stem yield and basal area over the measuring period.

The tree stand at Norrliden was, on average, 4.9 metres in height at the start of the experiment in the spring of 1971, with a variation between treatments from 4.4 m to 5.2 m. The number of stems per hectare varied from 1700 to 2100, with an average of 1940. Stand data are presented in the Appendix (Table 8.11) from the autumn of 1971 and from later measurements. In 1979 a small number of trees had to be removed, mainly from fertilised plots, because they had been damaged or even killed by snow-break. When volume production is discussed in the following, these trees are included in the production figures.

There is, as always, a within-treatment between-plot variation in all stand properties. Yet the analysis of covariance can be used for statistical adjustments of variation in tree growth measurements which can be related to initial differences in status. Use of initial (1971) values for stand basal area or volume usually explains 60 to 90 per cent of the variation in basal area or volume, respectively, at later revisions within either the group of 15 fertilised plots or the group of the 15 unfertilised plots. The degree of explanation (the R^2 value) decreases with time, but the partial correlation between the dependent variable and the one characterising the initial status has been statistically significant in all cases concerning unfertilised plots, while full significance was not obtained in some cases concerning the most extended periods on fertilised plots. We have tested several variables related to stand status at start as concomitant variables. In the case of basal area growth measured on increment cores, tests were made of both initial basal area and basal area growth during a period prior to treatments, with the highest correlation coefficient for the latter type of variable.

Data on basal area growth from Experiment E 57 Norrliden during 1972-1979 have been presented earlier by Tamm and Wiklander (1980) and in very condensed form by Tamm et al. (1984). It was concluded that acid application alone had a positive effect on tree growth, at least initially, but that there was a strong negative interaction between fertilisation and acidification. The positive effect was unexpected, even if similar effects have also been reported in Norwegian experiments with pine (Tveite, 1980; Abrahamsen et al., 1983; Abrahamsen, 1984; cf. also Stuanes et al., 1988).

The data now available make it possible to study tree growth, both basal area and volume growth, over a longer period than earlier and, thanks to the increment core

measurements, more accurately. Basal area growth is measured with higher precision on increment cores than with repeated calipering in the field and the possibility to measure annual ring growth before the start of the experiment further increases the accuracy of the measurements by providing good concomitant variables for calculation of adjustments with the analysis of covariance. This is particularly valuable when high time resolution is desirable, as in the study of time trends (next section).

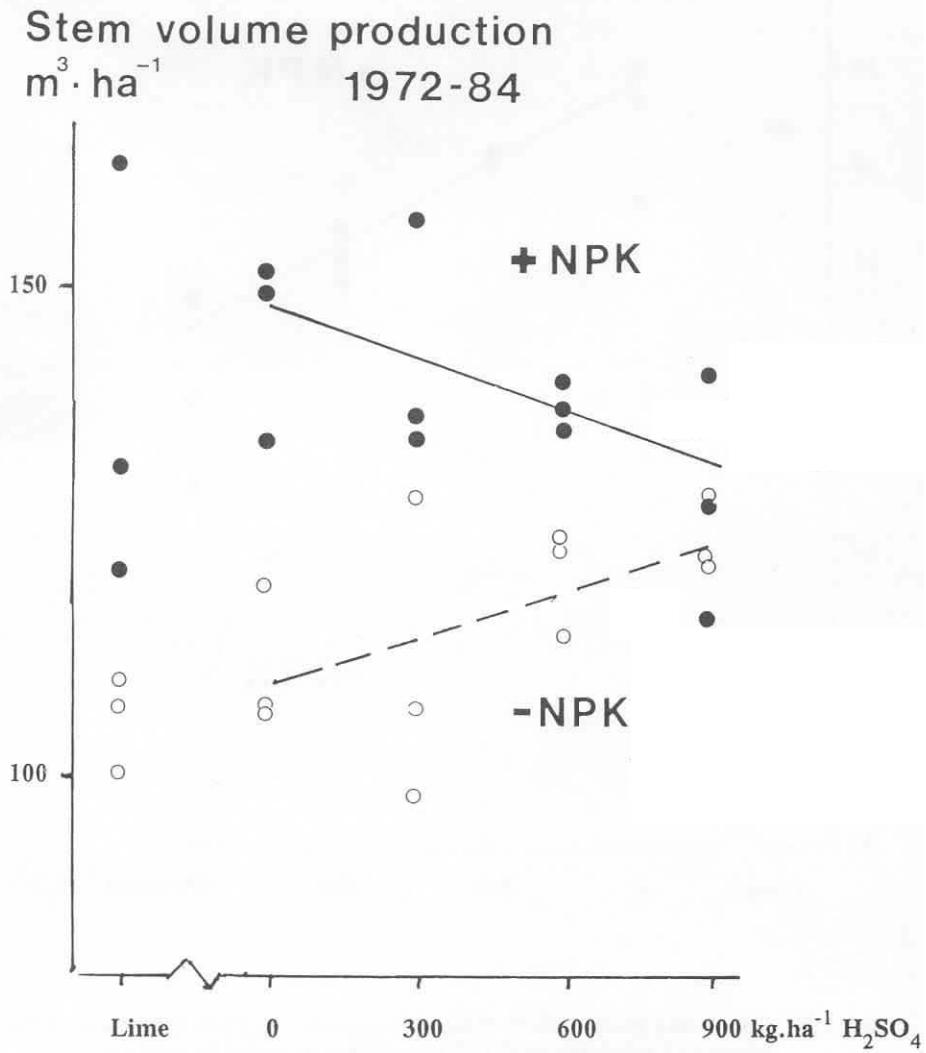


Fig. 3.14. Stem volume growth 1972-1984 in Experiment **E 57** as a function of the amount of sulphuric acid applied. Values adjusted by analysis of covariance for deviations from the mean in Bjørgung index (see text). Regression lines from the equations in Table 3.4.

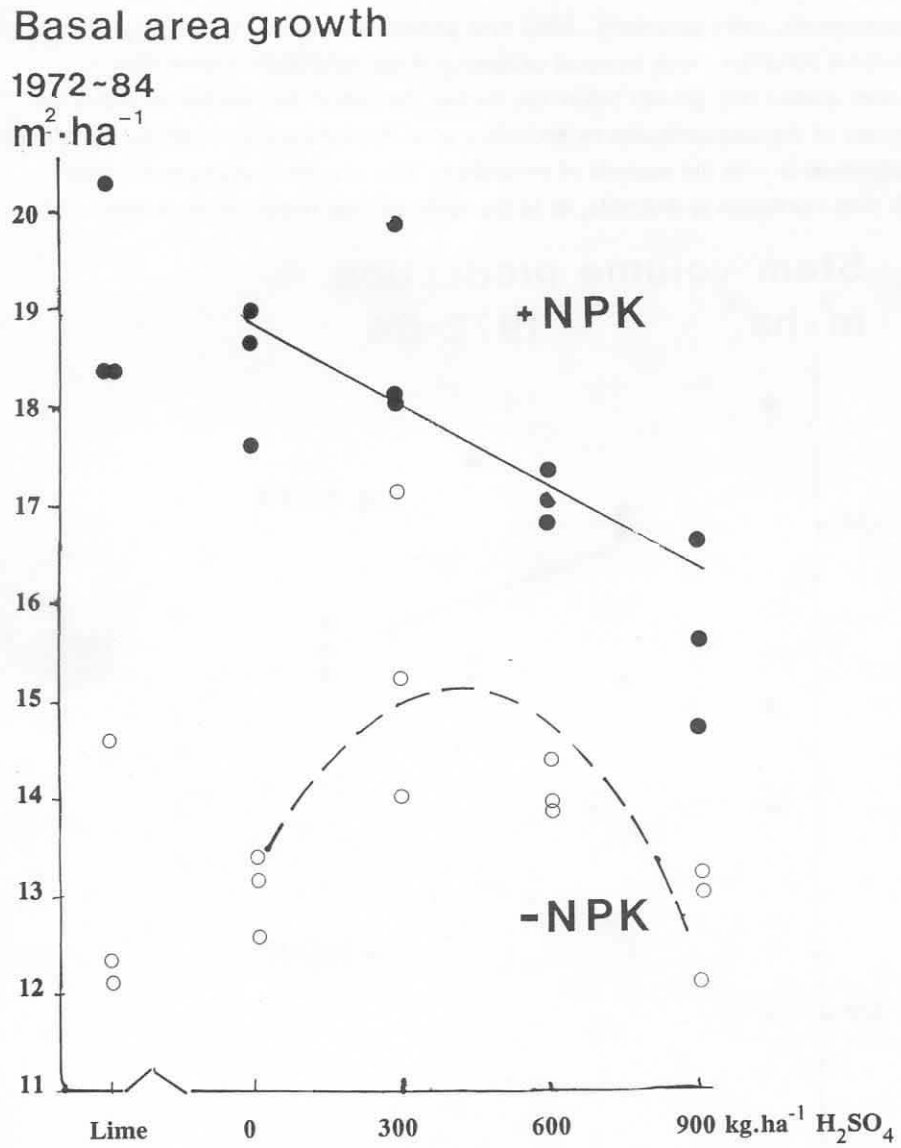


Fig. 3.15. Basal area growth, 1972-1984, in Experiment E 57 as a function of the amount of sulphuric acid applied. Values adjusted by analysis of covariance for deviations from the mean basal area growth, 1966-1970. Regression lines from equations in Table 3.5.

Fig.3.14. shows the total stem production during 1972 - 1984 in experiment E 57 as a function of the treatments, with adjustments made for initial differences in the so-called Bjørgung index, the square root of the number of trees per plot times the square of their average height (in 1970), $\sqrt{n} \times H^2$ (Bjørgung, 1968). Initial volume has also been tested as covariate, without much difference (somewhat lower R^2 values), but we have preferred to use the Bjørgung index in the analysis of covariance as it is completely independent of the treatments. As the first stand measurements were made in the autumn of 1971, some treatment effect on the trees of the applications in the spring could not be excluded. In the more accurate annual ring measurements for 1971 there is a difference (although not fully significant) in favour of the fertilised treatments. Table 3.4 presents a statistical analysis (Multiple linear regression) of the stem growth measurements in 1972 -1984. Statistical significance for effects of acid is obtained only for plots without NPK.

Fig. 3.15 shows the basal area growth as a function of treatments for the period 1972 - 1984, with basal area growth during 1966 - 1970 as adjustment variable in the analysis of covariance. The number of trees sampled was about 25, between one-half and one-third of the total number of trees within each plot. The corresponding statistical analyses are presented in Table 3.5, where treatment and concomitant variable explain almost two-thirds of the total variation in growth. For unfertilised plots, the treatment effect is significantly better fitted by a quadratic curve than by a straight line, while the difference between a straight line and a curved one is not fully significant for fertilised plots.

A further conclusion from Figs. 3.14 and 3.15 is that there is a strong negative interaction between the acid treatment and the fertilisation, apparent already in the diagram published earlier for the period 1972 - 1979 (Tamm & Wiklander, 1980).

Before further discussion we will look at the time development of both volume and basal area growth, but it should be noted in Figs. 3.14 and 3.15 that there is no clear indication of a response to liming, neither positive nor negative. It should also be noted that while the response to fertilisation amounts to about 35 per cent in stem volume and well over 40 per cent in basal area, the effects of acid are considerably lower, at most a decrease of about 15 per cent (on fertilised plots).

Table 3.4. Statistical analysis of stem volume growth over bark 1972-1984 (ΔV) as depending on acid application (ACID) and initial stand condition (BI, Bjørgung index).

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-value	P-value
A. -NPK					
Total variation	11	2939.3225			
Model	2	2243.6398	1121.8199	14.51	0.0015**
BI	1	1594.8516	1594.8516	20.03	0.0014**
ACID	1	648.7882	648.7882	8.39	0.0177*
Error	9	695.6827	77.2981		
B. +NPK					
Total variation	11	1363.0367			
Model	2	524.5003	262.2501	2.81	0.1123
BI	1	431.2496	431.2496	4.63	0.0599
ACID	1	93.2507	93.2507	1.00	0.3432
Error	9	838.5364	93.1707		

Equation A $\Delta V = 62.7968 + 0.2686(BI) + 0.01605(ACID)$ $R^2 = 0.7633$

Equation B $\Delta V = 102.8941 + 0.2499(BI) - 0.01795(ACID)$ $R^2 = 0.3848$

Table 3.5. Statistical analysis of basal area growth under bark 1972-1984 (BAG) as depending on acid application (ACID) and previous growth (BAG 66-70).

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-value	P-value
A. -NPK					
Total variation	11	23.4034			
Model	3	14.8912	4.9637	4.66	0.0362*
BAG_{66-70}	1	6.0390	6.0390	5.68	0.0444*
ACID	1	1.3832	1.3832	1.30	0.2872
ACID*ACID	1	7.4689	7.4689	7.02	0.0293*
Error	8	8.5123	1.0603		
B. +NPK					
Total variation	11	14.7040			
Model	2	9.3863	4.6932	7.94	0.0103*
BAG_{66-70}	1	3.0488	3.0488	5.16	0.0492*
ACID	1	6.3375	6.3375	10.73	0.0096**
Error	9	5.3177	0.5909		

Equation: A $BAG = 5.9130 + 1.9208(BAG_{66-70}) + 0.00931(ACID) - 0.0000114(ACID)^2$ $R^2 = 0.6363$

B $BAG = 15.3775 + 0.8828(BAG_{66-70}) - 0.0027(ACID)$ $R^2 = 0.6384$

3.3.2. Time trends in tree growth

Fig. 3.16 shows the annual basal area growth on (A) unfertilised, (B) fertilised, and (C) limed plots, always with the mean of the control plots as a solid line without symbols. Fig.3.16 A confirms the result from Figs. 3.14 and 3.15 that there has been a slight positive reaction to Acid 1 and Acid 2, persisting most of the period, while Acid 3, from a start above the control curve, falls slightly below the control for most of the period after the end of the acid applications (1976).

Fig. 3.16 B clearly shows the strong positive reaction to fertilisation, but also that the difference between NPK plots and controls decreases from about 1975. The curve for treatment Acid 3 + NPK falls more rapidly than those for other NPK treatments with or without Acid. Fig. 3.16 C, finally, demonstrates again what could be seen in Figs. 3.14 and 3.15, viz., that there is little effect so far from liming on basal area growth.

The same time trends as in Fig. 3.16 are also demonstrated in Fig.3.17, in another way, as relative basal area (with the mean of the controls set as 100 per cent). This way of illustrating the trends has the advantage of integrating the data over time. It shows, for instance, that the growth produced in the initial positive reaction such as that for the NPK treatment is not lost with time, unless there is a subsequent negative reaction (convergence of curves). Parallel curves mean similar growth rates. On the other hand, it is evident that small differences in original level (prior to treatments) such as the difference between NPK and Lime + NPK in Fig. 3.17 C, tend to have long persistance. Such differences can be interpreted as inherent differences in site quality between plots and treatments which have not been removed by the statistical adjustment, i.e., they do not affect the covariate in the same way as they affect later growth. However, changes in slopes between the curves are more informative than changes in level, and looked upon in this way the curves in Fig. 3.17 give an illustrative picture of the trends described.

As mentioned earlier, field measurements of stem volume are less accurate than basal area measurements. Yet curves for stem volume development (Fig.3.18) confirm what has already been said, viz. that the effects of acid application are smaller than the fertiliser effect, but also that the effects of both treatments are moderate at the Norrliden site, corresponding to, maximally, some years enhancement or delay. Also the control plots show, at this age, a growth rate which must be considered as very satisfactory for the North-Swedish inland. There is, for unfertilised plots, even a slight tendency for stem growth to increase with age during the period 1979 to 1987, i.e., at tree ages from 28 to 36 years.

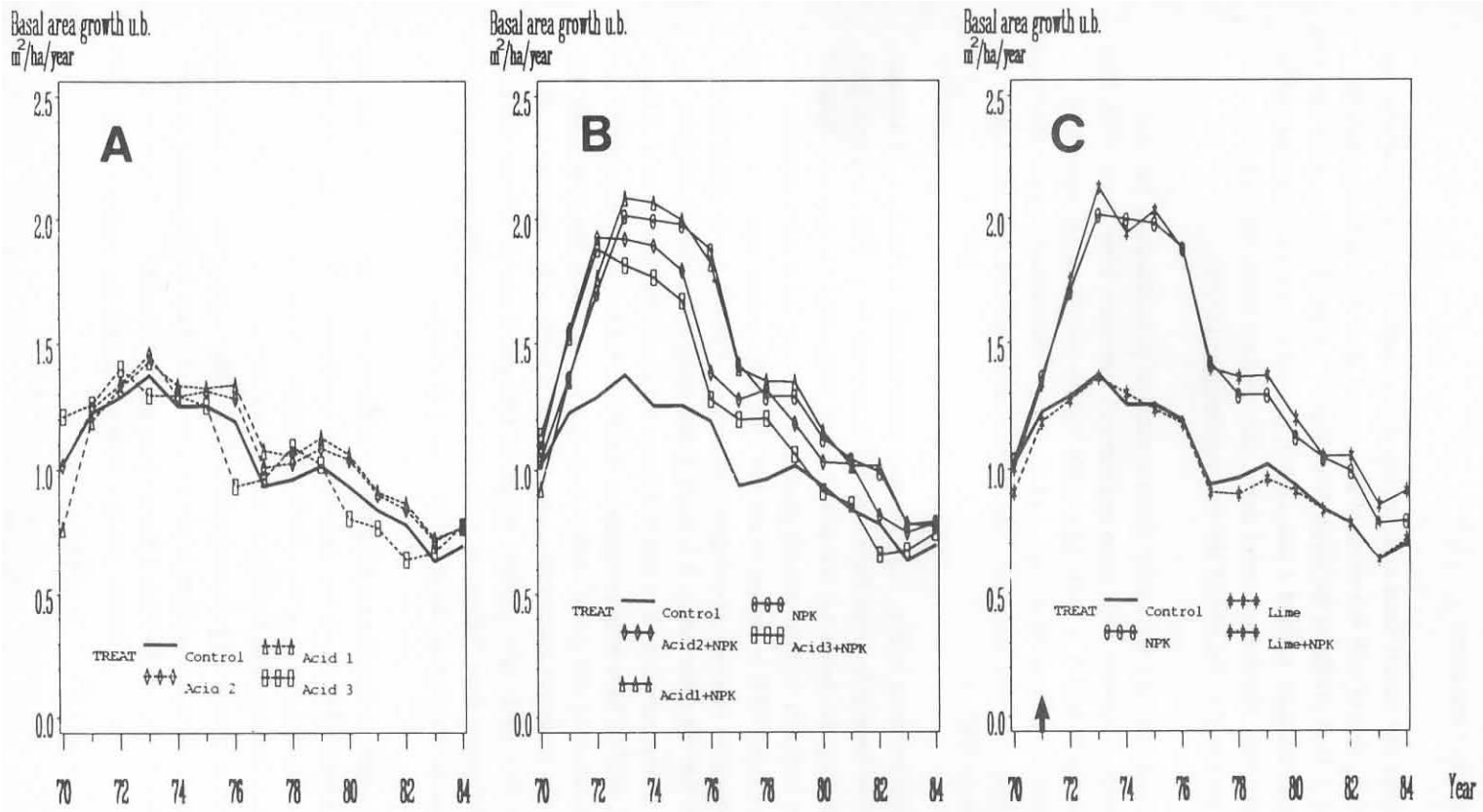


Fig. 3.16. Annual basal area growth under bark in Experiment E 57. **A:** Treatments without NPK, with and without acid. **B:** Treatments with NPK, with and without acid. **C:** Treatments with lime, compared with NPK only and control.- All values are adjusted with analysis of covariance for differences in basal area growth in 1967-1969, before treatments. The arrow in Fig. C marks the year of liming.

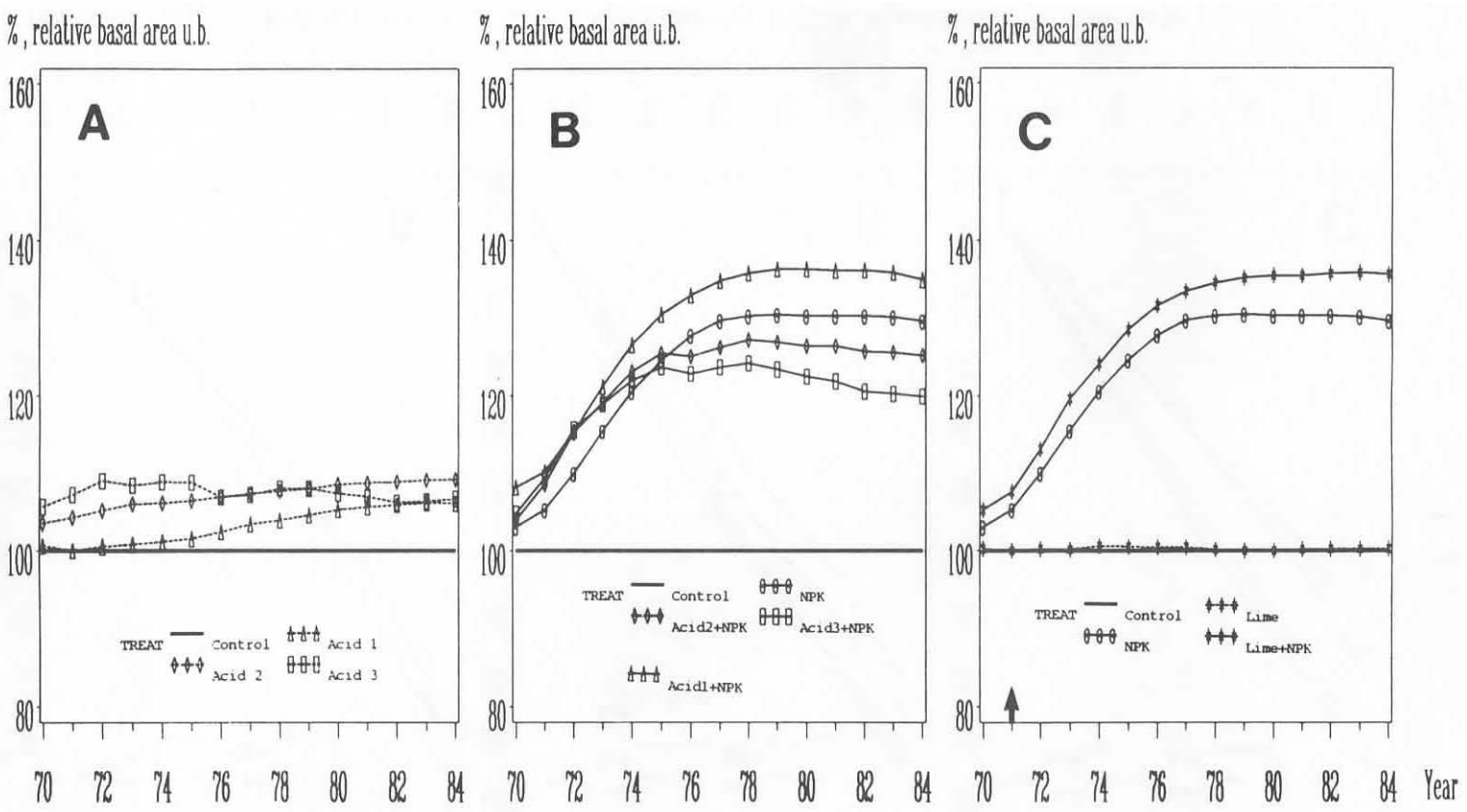


Fig. 3.17. Relative basal area under bark in different years in Experiment **E 57.** Average for controls set to 100. **A, B, and C** as in Fig. 3.16. Adjustment for differences in previous growth as in Fig. 3.16.

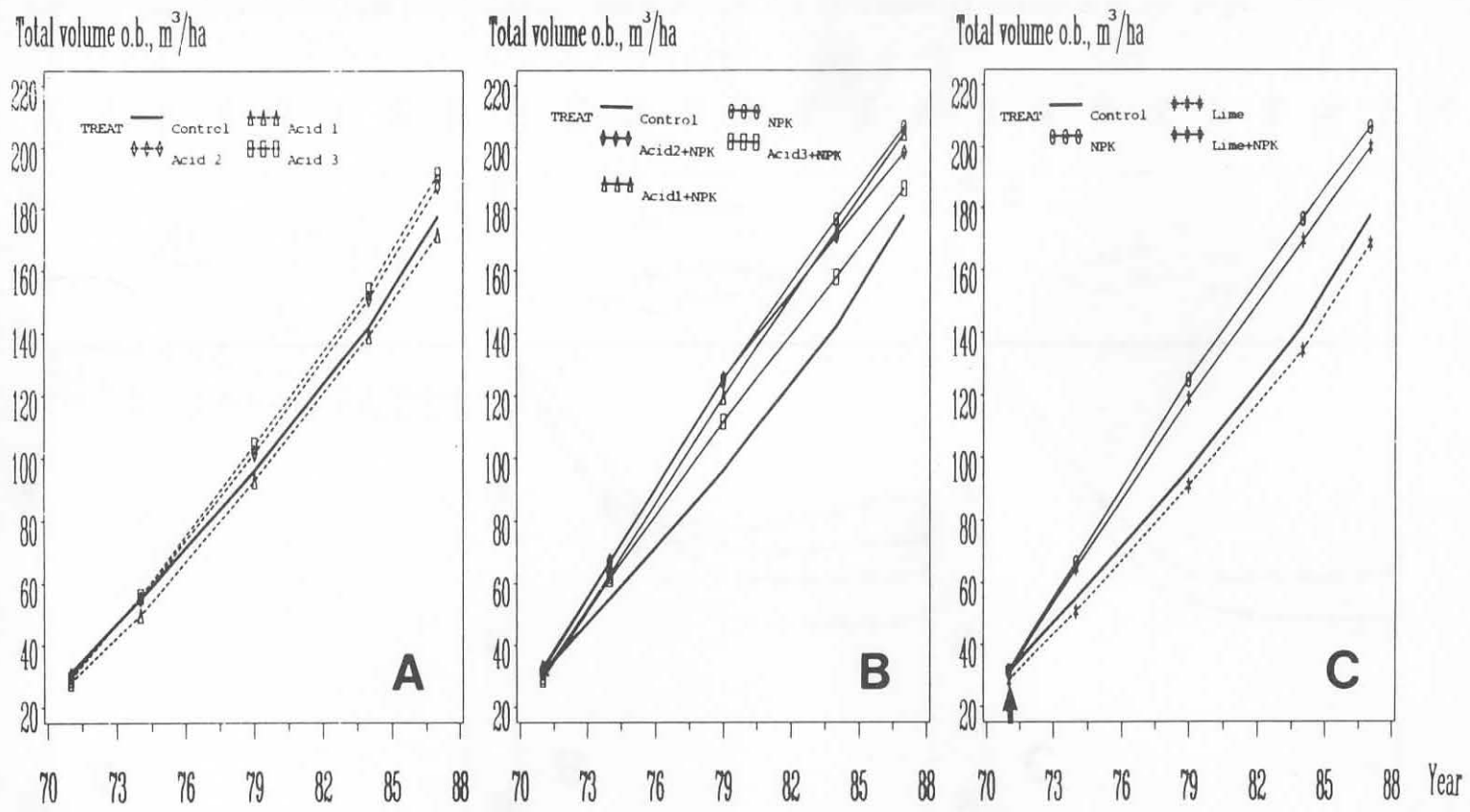


Fig. 3.18. Total stem production over bark, m^3 per ha, in Experiment **E 57. A, B,** and **C** as in Fig.3.16. Values adjusted for differences in initial stand conditions using Björgung's index (see text) as covariate.

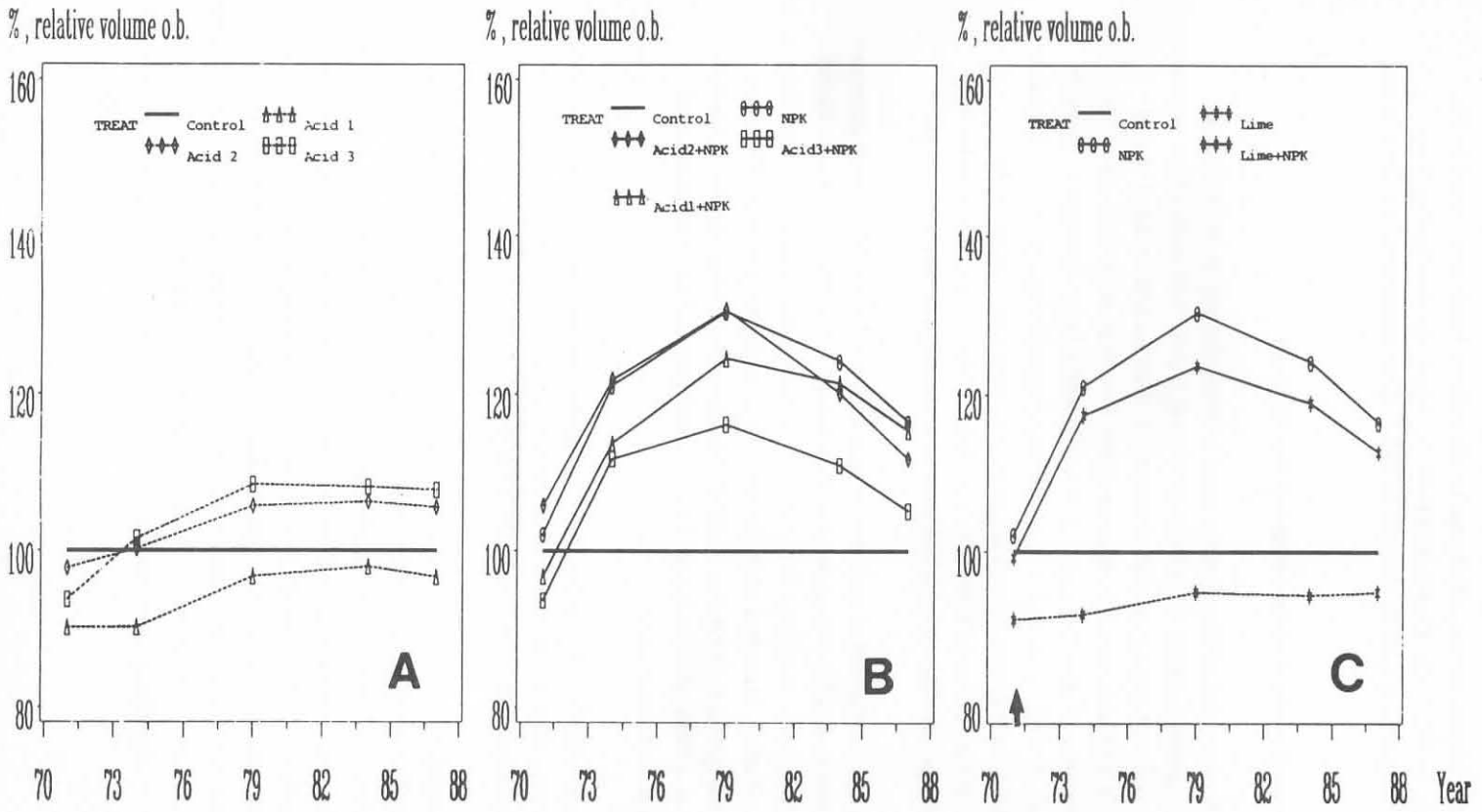


Fig. 3.19. Relative stem volume over bark in different years in Experiment **E 57.** Average for controls set to 100. A few trees removed in 1979 because of damage are included in the total volume. **A, B,** and **C** as in Fig.3.16. Adjusted values (see Fig.3.18) used.

Relative stem volume curves, analogous to the relative basal area curves in Fig.3.17, are presented in Fig.3.19. They confirm on the whole the conclusions from Fig.3.17, if the main emphasis is laid on changes in curve slope rather than on curve levels.

3.3.3. Summary of results from the tree growth measurements

The number of degrees of freedom for error is relatively low in the statistical analysis of treatment effects on various growth measures. And even where measurements at different points in time give similar results, it must be kept in mind that in time series of measurements one data set is not independent of other sets. The statistical analyses (Tables 3.4 and 3.5) have therefore been restricted to the stem growth data (cf. Figs. 3.14 and 3.15), with the diagrams Figs. 3.16 - 3.19 used to illustrate the growth effects over time, as well as their size relative to the controls at various points in time. The conclusions that we are able to draw with some confidence are thus limited, but may be formulated as follows:

1. There is a well-established negative interaction between the NPK fertilisation and the experimental acidification applied in Experiment E 57. The negative deviation from treatment NPK when also either Acid 2 or Acid 3 was added has, according to the field measurements, increased after the end of the application of acid. The more accurate basal area measurements confirm this conclusion, although the deviations interpreted as effects of Acid appear to start somewhat earlier in the basal area than in the field measurements.

2. The lowest acidification regime (Acid 1) has not had any measured adverse effect on tree growth, whether on fertilised or unfertilised plots. A slight positive effect can not be excluded, not even on fertilised plots.

3. On unfertilised plots, the field measurements early indicated a positive growth reaction for acid (period 1972-1979). This reaction is confirmed for the volume growth during 1972-1984, with the additional comment that the growth rates for both controls and acid treatments have been very similar since 1979, judging from the field measurements. The interpretation of the time curves for relative basal area and relative stem volume is somewhat complicated by differences in start levels of certain treatments (Acid 2 and Acid 3 on one hand and control and Acid 1 on the other in the case of relative basal area). Yet it is clear from both field and ring measurements that the positive reaction did take place mainly during the time of acid application.

4. No clear effect of liming on tree growth was observed from either field or ring measurements. The curves for the treatments NPK and NPK + Lime differ slightly in the diagrams of relative volumes and relative basal area, but in opposite directions, so the diagrams merely illustrate a point made earlier, that small differences in level in this type of diagram tend to persist over long periods. The slight differences between the two types of measurements with relation to liming should probably not be given too much attention, but it should be remembered that both liming and nitrogen fertilisation decrease the needle boron content to levels where some damage (top die-back) may be expected (Aronsson, 1983) and indeed has been observed. Even less obvious retardation of top growth might change the relation between basal area growth and stem volume growth.

We shall return to the tree growth results in the concluding Section (3.5), but it should be remembered that the present acid deposition in Scandinavia supplies both sulphur and nitrogen compounds, let alone that this airborne nitrogen fertilisation is less intensive in Sweden than that used in our acidification experiments. The results from fertilised and acidified treatments should, however, be at least as relevant for the discussion as those from plots with acidification only.

3.4. Changes in vegetation and soil organisms

There have been marked vegetational changes on most of the treatments in Experiment E 57. These will be described in detail in a separate paper by Dirkse et al, and here only short indications will be given of the type of changes (see also Dirkse and van Dobben, 1989).

NPK fertilisation has gradually destroyed most of the dwarf shrubs, mosses and lichens occurring before treatment and still surviving on the control plots (and to a large extent also on the limed plots). Instead, existing grasses, mainly Deschampsia flexuosa, have increased and spread, as has Epilobium angustifolium, where only very scattered individuals had survived from the reforestation phase, but where extensive new colonisation has occurred after fertilisation. As the fertilisation also increased needle biomass and shading, parts of the plots have become so dense that field layer vegetation is more or less shaded out. The original mosses and lichens are also gone to a large extent, leaving large areas without a bottom layer.

Acid application caused immediate damage to the vegetation, particularly when applied in larger amounts. Since the last acid application in 1976 a considerable recovery has occurred, and the Acid 1 plots do not differ much from the controls, while Acid 2

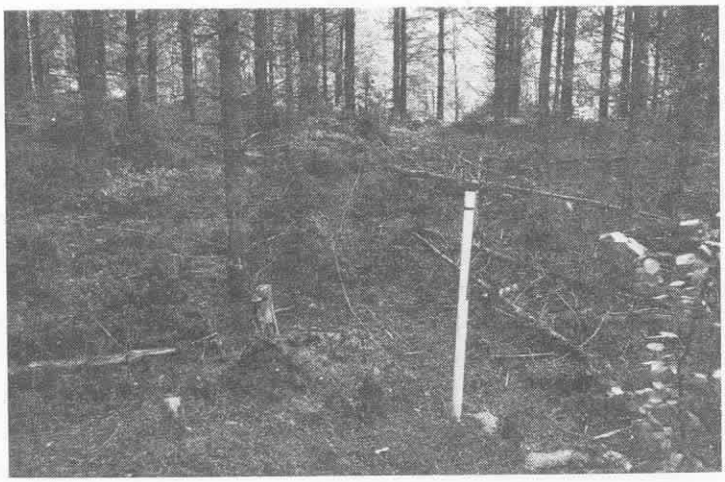


Fig. 3.20. The boundary between plot 6 (Control), to the left, and plot 5 (Acid 3), to the right of pole. Experiment E 57, September 1980.

Fig. 3.21. Plot E 57 No. 26 (NPK+Acid 3) in September 1980.

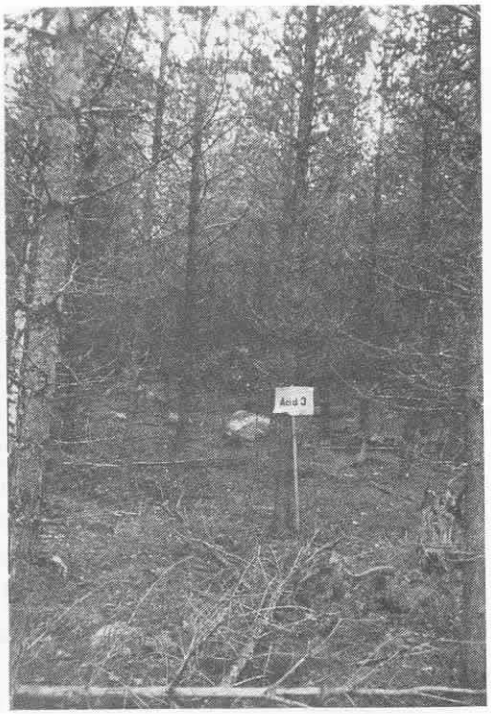


Fig. 3.22. Plot E 57 No.27 (Acid 3) in September 1980

and Acid 3 plots still have less coverage of both dwarf shrubs and bottom layer. The limed plots do not look very different from the controls either, even if initially there were effects especially on lichens.

The combination of NPK with either acid or lime had initially the strongest effects on the vegetation, but since the acid application was discontinued in 1976, there seems to be a convergence with the plots with NPK alone.

The vegetation effects observed are, for NPK, similar to those observed in other intensive fertilisation experiments, with the "normal" forest vegetation more or less completely replaced by species characteristic of cleared areas. The effects of acid application have consisted in direct destruction of much of the existing vegetation, with a partial recovery after the end of the acid applications. On the whole, the role of field and bottom layer vegetation decreased as a consequence of the acid treatment (Fig.3.20 to 3.22). It thus cannot be excluded that decreased competition from lesser vegetation has contributed to the positive growth response in the trees to acid. The relatively low biomass of the field layer makes it difficult to decide whether the role of this decreased competition has been important.

3.5. Discussion and conclusions.

The final conclusions from both the Norrliden and the Lisselbo experiments will be drawn in the final chapter, Section 5. However, here it may be pointed out that although the acid treatment may have been an "unnatural" disturbance of the forest ecosystem, the trees tolerated the treatment, and may even have had a temporary advantage of decreased competition.

The acid treatments had acidified the mineral soil horizons (0 - 20 cm down) at the sampling nine years after the last acid application. The humus layer acidification at that time was not statistically significant but had been observed earlier (Table 3.1, cf. also Bååth et al., 1980; Lohm et al., 1984). The mineral soil acidification consisted of decreased pH (0.1 - 0.4 units) and decreased base saturation, connected with losses of calcium and, in particular, magnesium. Foliar analysis showed surprisingly small effects of the acidification, but a tendency for magnesium concentrations to be lower could be noted.

Tree growth was positively affected by the acid application, but the effect was much smaller than for NPK.

Continued NPK additions (also after the end of the acid application) had much stronger effects than the acid on both soil, vegetation, and trees as measured in 1984. The strong acidification of the mineral soil is most remarkable (while the humus layer became less acid, and also increased in weight and content of nitrogen and exchangeable calcium). NPK fertilisation increased needle nitrogen concentrations, as expected, but lowered the concentrations of most other nutrients, in spite of the PK additions. Again, magnesium tended to decrease in both soil and needles. In the soil there is a negative interaction of NPK x Acid in the case of exchangeable magnesium, one of the few significant interaction effects found in the soil data.

In tree growth there was a strong negative interaction of NPK x Acid (both NPK and Acid increasing growth when alone, but Acid more or less neutralising the NPK effect).

The liming effects on the soil chemical data are strong, but always in the direction expected (Hallbäcken & Popovic, 1985; Derome et al., 1986). The effects on foliar concentrations (except calcium) and tree growth were small, if any.

4. EXPERIMENT E 42 LISSELBO.

Results and discussion

4.1. Soil analyses and incubation experiments.

Although sedimentary soils such as glacifluvial and outwash sands often carry rather uniform tree stands and a species-poor field layer vegetation, this is no guarantee that the soil is homogeneous with respect to texture and water-holding capacity. At Lisselbo there is a gradient from the top of the esker, where wave action during the postglacial land upheaval has removed part of the finer material (fine sand and sand), leaving more of the stones and gravel from the original glacifluvial deposit. The finer material has then been redeposited lower down. Fig. 4.1 shows the textural composition of the B horizon in three sample pits, representing a gradient from the top of the esker (plot 60 at top, plot 62 middle slope, and "plot 26", a plot left out of the blocks because of its position at the low end of the slope (adjacent to plot 27, Fig.2.4), representing a somewhat different topographic position. As can be seen in the Appendix, Table 8.17, there is also a variation in the stoniness index and hence material < 2 mm between plots, also connected with the topographical gradient. Sand (0.2 - 2 mm) is the dominant fraction in all plots (Fig.4.1, 4.2).

The whole area is well-drained, or (according to some terminologies), excessively drained, with 3 - 4 m depth to the groundwater in the lowest parts and more than twice as much in higher parts. We have not measured depths of the deepest roots, but considered the young stand at the start of the treatments (1969) as completely unaffected by groundwater and the capillary zone. As it is known that old trees of Scots pine may have occasional roots at depths down to at least 3.25 m in well-drained sandy soils (O.Tamm 1937), it is possible that some tree roots have now reached the capillary zone even if there is no evidence in this direction (see below in the discussion of the results of the irrigation treatment, section 4.3).

The experimental area was divided into ten blocks, of which experiment E 42 comprises blocks 9 and 10. The random distribution of treatments within Experiment E 42 resulted in an allocation of the two control plots in these blocks at the top of the esker and adjacent to each other. The stand properties in 1968, which were used in our attempts to create as homogeneous blocks as possible, did not differ systematically along the topographic gradient described, but later studies revealed the textural differences mentioned. Therefore, we have considered the irrigated plots as being more representative for untreated areas than the original controls, and have used them, marked "Acid 0", with quotation marks, in the presentation of the results

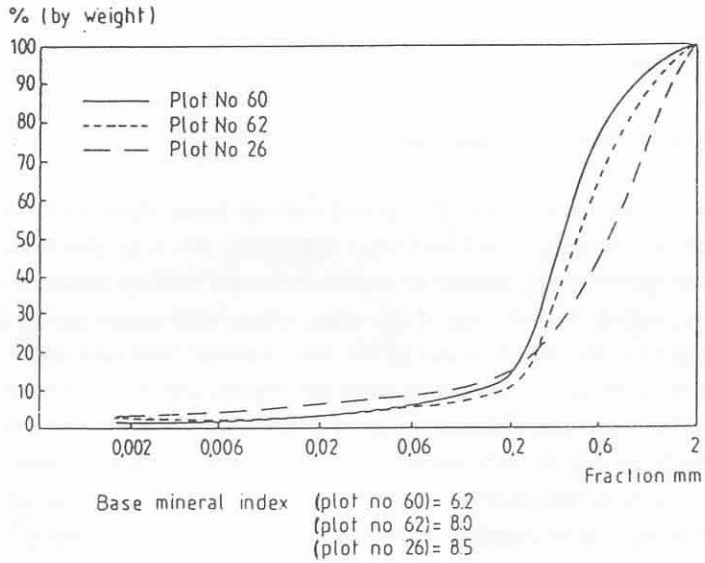


Fig. 4.1. Soil texture (fraction < 2 mm) of three B horizon samples from **Lisselbo** (plots No. 60, 63 and 26 along a gradient from the top of the esker; plot 26 is an extra control adjacent to plot 27 in Fig.2.4.). The curves show the accumulated amounts of particles below the diameters noted on the X-axis. The base mineral index of the samples is noted at the bottom of the diagram.

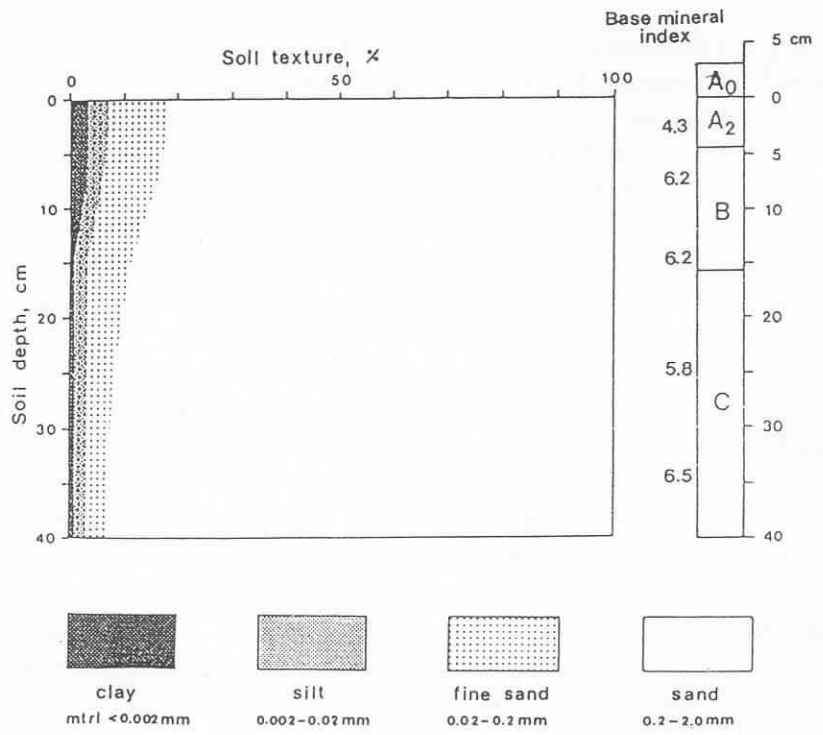


Fig. 4.2. Variation of soil texture (<2 mm) and base mineral index with depth in a **Lisselbo** soil profile (control plot No.60). Soil horizons to right. From Hallbäcken & Popovic, 1985.

Table 4.1. Expt **E42, Lisselbo.** Comparison of soil data for the plots of treatments 0 and Irrigation ("Ac 0") at the 1976 sampling.

	Humus layer(A_0)		0–5 cm Mineral soil	
	0	Irrig.	0	Irrig.
Titratable acidity TA µeq/g	532 558	470 530	56.7 42.9	56.7 45.2
Sodium Na µeq/g	2.6 2.3	2.0 2.2	0.1 0.1	0.2 0.1
Potassium K µeq/g	7.5 7.4	6.0 7.9	0.6 0.5	0.6 0.7
Calcium Ca µeq/g	77.2 88.7	86.7 87.4	1.9 1.8	4.8 1.5
Magnesium Mg µeq/g	11.0 11.2	12.8 13.2	0.4 0.5	1.1 0.4
Base saturation V%	15.6 16.4	18.6 17.3	5.2 6.3	10.6 5.6
Total nitrogen N%	1.01 1.19	0.87 1.06	- -	- -
Loss on ignition %	54.9 51.6	50.8 55.8	- -	- -
Dry weight A_0 (1976) 10^3 kg/ha	55.9 44.1	37.1 42.6	- -	- -
Plot number			55 60	73 65
Stoniness index (1985)			11 10	30 20
Estimated dry weight 0–20 cm, mineral soil, 10^3 kg/ha (1985)			970 920	1928 1424

of the soil sampling in 1985. None of our comparisons of soil data between the original controls and "Acid 0" (Table 4.1, see also Appendix, Table 8.12) has shown systematic differences in qualitative chemical properties. The stoniness index and hence the weight per hectare of the soil <2 mm of "Acid 0" is within the same range (16-30cm) as all the other treatments, while both original control plots are outside this range (10 and 11, respectively). Use of data from the latter plots might thus lead to misleading estimates of fertiliser and acidification effects. As will be discussed in section 4.3, any growth response that may have occurred to the rather limited amount of water added during 1970 - 1976 (altogether 420 mm or, on average, 60 mm per summer, with water from an oligotrophic lake, see Tamm et al., 1974) had ended long before the soil sampling in 1985.

As our data will show, most of the acid effects on soils and tree nutrient levels are below formal significance levels. This is not surprising in a field experiment of pilot character, with only two replicates of each treatment. We shall therefore only discuss the results briefly, with the possibility for the reader to look into the details in the Tables 8.12 - 8.21 in the Appendix. Most of the trends observed agree with those already discussed in Experiment E 57 Norrliden, which was laid out two years later, but with a more satisfactory number of replicates and levels of acid.

The pH measurements (Tables 8.12 and 8.13) made on different occasions at Lisselbo provide very little evidence of any effect of the treatment Acid 1 on soil pH, while treatment Acid 2 may have depressed pH in the humus layer by 0.1 - 0.2 units and a little more in the mineral soils in 1976. The differences are not significant in the single samplings, but fairly consistent in the horizons sampled. The liming has increased the pH not only in the humus layer but also in the mineral soil, although with a delay. The October 1976 values for acidified plots, which are often lower compared with the May values (in the mineral soil), might be influenced by the 1976 acid application, given after the May sampling.

Other soil acidity variables than pH are shown in Table 8.13 and suggest that, in 1985, base saturation is lower with Acid 2 than on comparable plots without acid, while it is clear that not only liming but also NPK fertiliser increases base saturation. As in the case of pH, Acid 1 does not deviate much from "Acid 0". On the other hand, titratable acidity does not seem to have been much affected by either acidification or fertilisation (but decreased by liming). Table 8.14 suggests that if the lowering in base saturation (V%) with Acid 2 is real the cations lost would primarily be calcium ions, accompanied by some magnesium ions. Unlike the pH changes, the cation losses are larger in the humus layer than in the mineral soil. The data on exchangeable aluminium and sulphate (Table 8.15) do not give any clear

picture of the effects of acid and fertilisation, while it is clear that lime depresses the concentrations of exchangeable aluminium. The carbon/nitrogen ratios in the humus layer (Table 8.16) are fairly similar to those at Norrliden (Table 8.6), without clear relation to the treatments. There is a tendency towards higher C/N ratios in the mineral soil at Lisselbo than at Norrliden.

The analytical results have also been recalculated to amounts per hectare, and summarised for the mineral soil horizons (Tables 8.17 - 8.21). The same tendencies (or lack of tendencies) as described for the concentration data are found also for these data. It can be noted that the much poorer site at Lisselbo has stores of carbon and nitrogen of the same order of magnitude as Norrliden down to 20 cm depth in the mineral soil. It seems likely that there is somewhat more of these two elements in the deeper horizons at Norrliden, as 20 cm is in the middle of the B horizon there, while the Lisselbo profiles have a thinner A2 horizon. Consequently, a sampling down to 20 cm includes more of the B horizon at Lisselbo than at Norrliden.

The difference in nitrogen content between fertilised and unfertilised plots (down to 20 cm in Table 8.18) is 255 kg per ha, an increase of 33 per cent, which corresponds to 25 per cent of the 1040 kg nitrogen applied. The corresponding calculation can be made for the Norrliden data in Table 8.8 and gives a difference of 234 kg nitrogen, an increase of 23 per cent and a "recovery" of 21 per cent of the added nitrogen. There is a possibility that the lower B horizon (below sampling depth) at Norrliden retained more nitrogen than the B/C horizon at the same depth at Lisselbo, which would decrease or even reverse the difference. Experiment E 55 at Norrliden has shown a slightly higher "nitrogen recovery" than E 57 at the N2 level (22 per cent in 1988), and much higher values at the N1 level (48 per cent, Tamm et al., in prep.).

In 1971 and 1976 humus samples were collected for incubation experiments in the laboratory. The 1976 series has been reported by Popovic (1984) together with similar studies for samples from Experiments E57 Norrliden and E63 Åseda. It was concluded that acidification had less effect on ammonification and nitrification at Lisselbo, than at the two other sites. Liming depressed nitrogen mineralisation during incubation, except on one fertilised plot, the only one where nitrification occurred (Table 4.3). NPK fertilisation caused slightly higher start concentrations of inorganic nitrogen (as ammonium N) and stimulated nitrogen mineralisation (almost entirely as ammonium N). The results from the earlier incubation (Table 4.2), when treatment Acid 2 had been given for two years and Acid 1 for one year only, confirm the absence of a clear response to acid application and the positive effect of the fertiliser treatment, while three of the limed plots (the two fertilised and one

Table 4.2. Expt E42, Lisselbo. Inorganic nitrogen as % of total N (Kjeldahl) in humus samples from differently treated plots at sampling and after six and nine weeks of incubation. Sampling in May 1971.

Treatment	Plot No	Total N kg/ha	Inorganic N % of total N weeks 0	6	9
Control	55	440	0.11	0.24	0.24
	60	252	0.24	0.30	0.31
Irrigation	73	252	0.14	0.28	0.42
	65	475	0.11	0.23	0.24
Acid 1.	63	331	0.14	0.36	0.33
	72	344	0.27	0.70	1.20
Acid 2.	69	383	0.14	0.24	0.55
	57	363	0.11	0.26	0.26
Lime	62	329	0.46	1.40*	2.17*
	58	484	0.15	0.34	0.25
N P K	66	297	1.19	1.36	0.90
	61	486	0.69	1.01	0.71
" +Irr.	54	475	1.18	1.32	1.60
	59	350	0.75	1.54	1.41
" +Ac 1	70	750	0.99	0.46	0.65
	64	377	0.81	1.07	1.37
" +Ac 2	67	-	0.64	1.29	1.56
	56	311	0.55	1.02	1.08
" +Lime	68	405	1.05	2.33*	3.22*
	71	585	0.77	1.12*	1.52*

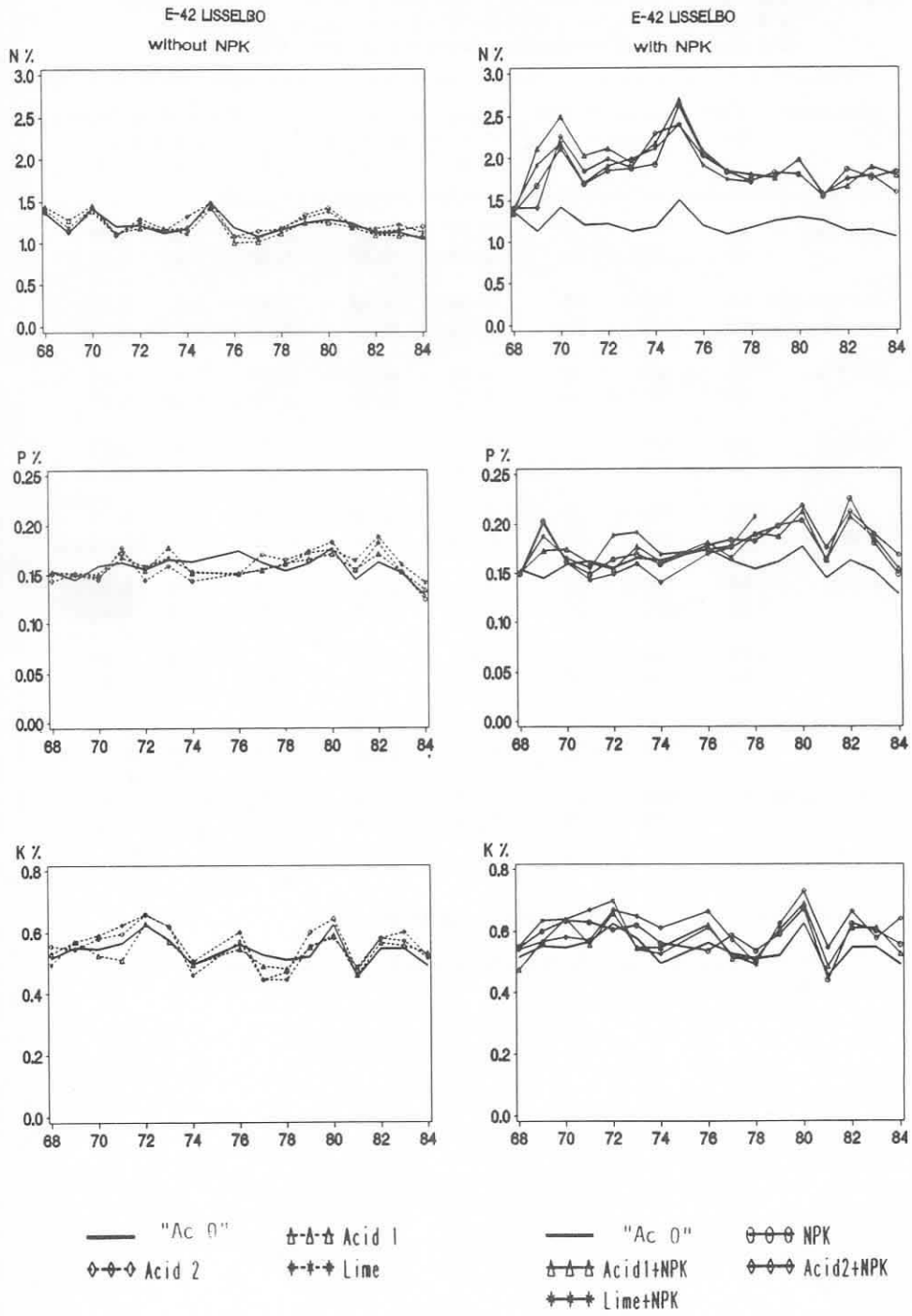
* In samples marked with asterisks, most mineral N was nitrate-N, which only occurred in small amounts (< 5 per cent of mineral N) in other incubated samples.

Table 4.3 Expt **E42**, Lisselbo. Inorganic nitrogen as % of total N (Kjeldahl) in humus samples from differently treated plots at start and six and nine weeks of incubation. Sampling in May 1976.

Treatment	Plot No	total N kg/ha	C/N ratio *	Inorg. N % of total N weeks 0	6	9	CO_2-C % of C*-tot. weeks 6	9
Control	55	565	36	0.05	0.67	2.66	3.42	4.89
	60	525	34	0.03	0.42	1.52	3.34	4.61
Irrigation	73	323	38	0.08	0.48	2.70	3.67	5.53
	65	452	36	0.04	0.15	0.52	4.03	5.52
Acid 1.	63	416	42	0.04	0.18	1.47	3.47	4.66
	72	282	43	0.10	0.24	1.59	3.39	4.97
Acid 2.	69	434	35	0.13	1.72	5.29	3.43	5.13
	57	331	44	0.11	0.23	1.26	3.09	4.73
	62	369	37	0.07	0.08	0.18	5.06	6.50
Lime	58	389	35	0.03	0.13	0.18	5.14	6.63
N P K	66	530	36	0.81	2.46	2.59	2.93	4.09
	61	582	29	0.87	1.87	4.78	2.92	3.97
" +Ac 1	70	566	43	0.84	1.65	2.91	2.34	3.49
	64	556	30	0.55	1.17	3.88	3.22	4.62
" +Ac 2	67	538	33	0.50	0.79	2.51	2.95	4.10
	56	535	38	0.83	1.55	5.93	3.09	4.73
" +Lime	68	461	31	1.25	0.42	0.32**	6.34	7.89
	71	470	39	0.68	3.52	7.04**	2.81	3.72

* carbon is calculated from loss on ignition

** most N-inorg. was nitrate-N in this sample (nitrate-N was low in all other samples)

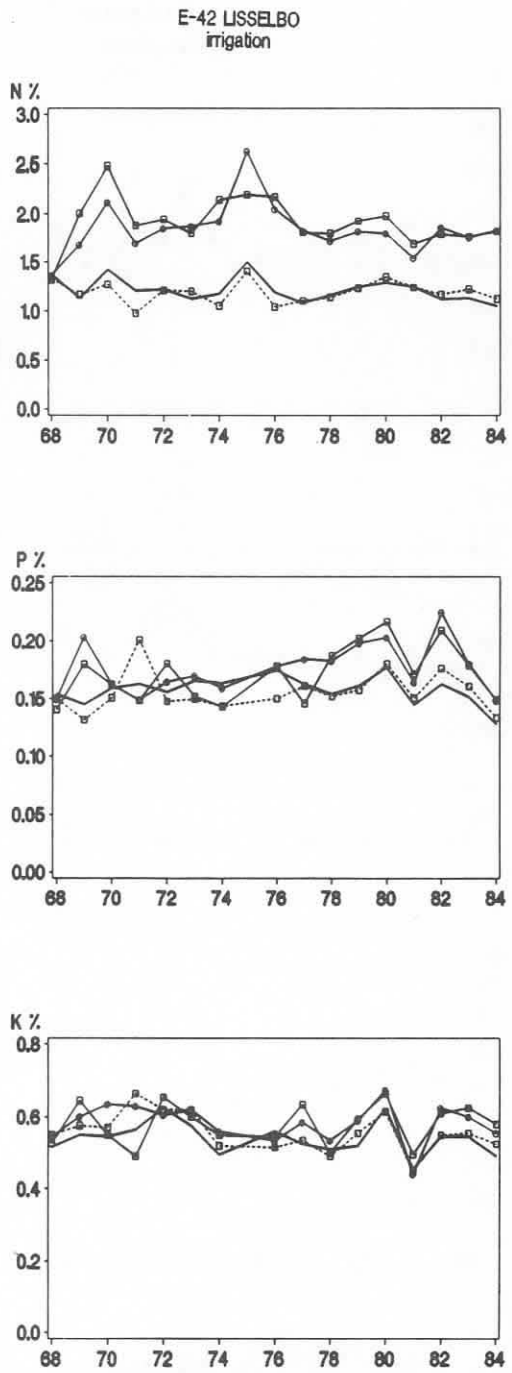

E-42 LISSELBO
without NPK
E-42 LISSELBO
with NPK
N %
P %
K %
"Ac 0"
Acid 1
Acid 2
Lime
NPK
Acid1+NPK
Acid2+NPK
Lime+NPK

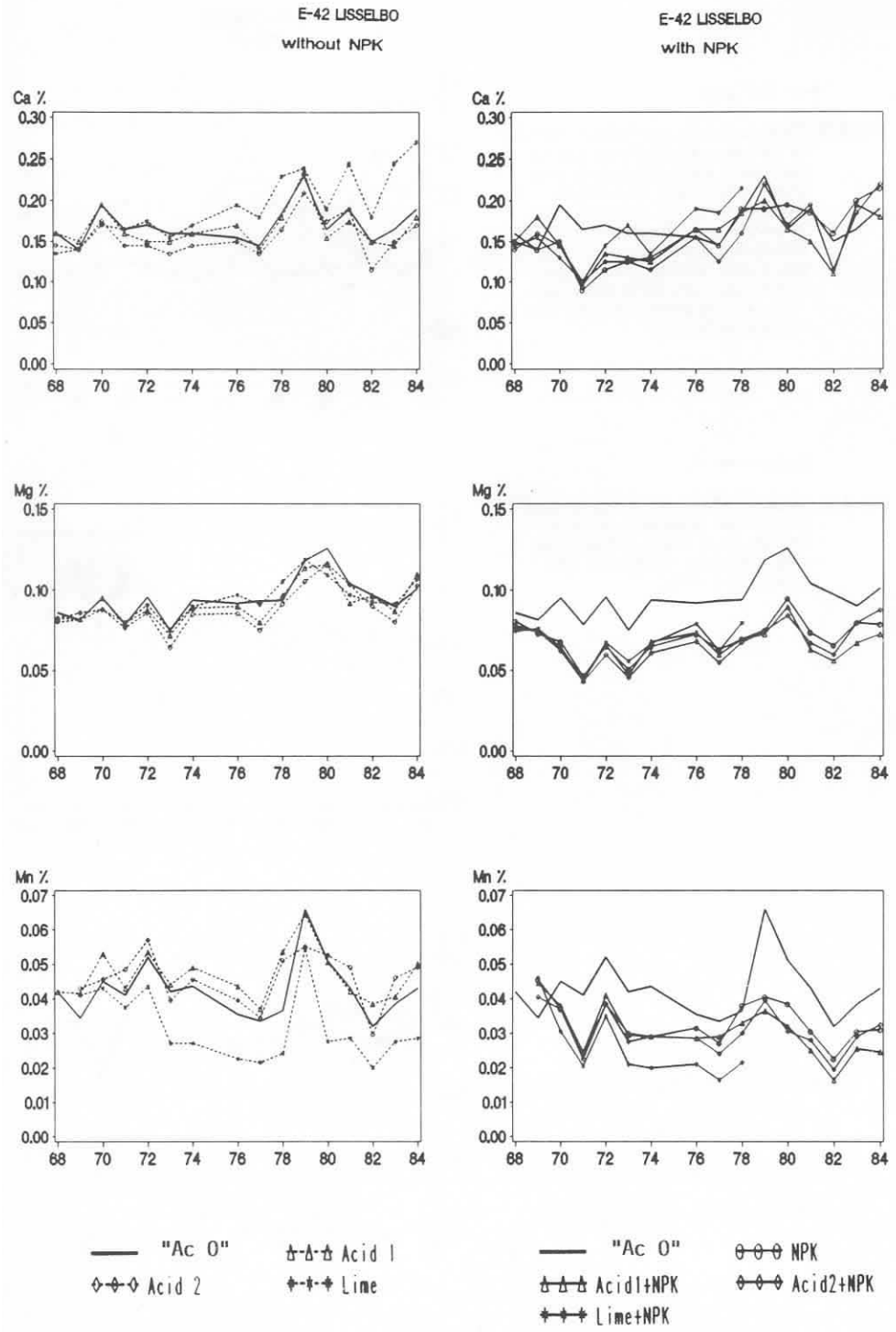
← Left page

Fig.4.3. Concentrations (per cent of D.M.) of nitrogen, phosphorus and potassium in exposed current pine needles harvested annually in October from the same ten trees in each plot of Experiment E 42. Means for duplicate plots. Left: treatments without NPK, right: treatments with NPK (plus the "Acid 0", marked as a solid line without symbols).

Right →

Fig.4.4. Concentrations of nitrogen, phosphorus and potassium in pine needles as in Fig.4.3, but from irrigated plots, compared with control and NPK.



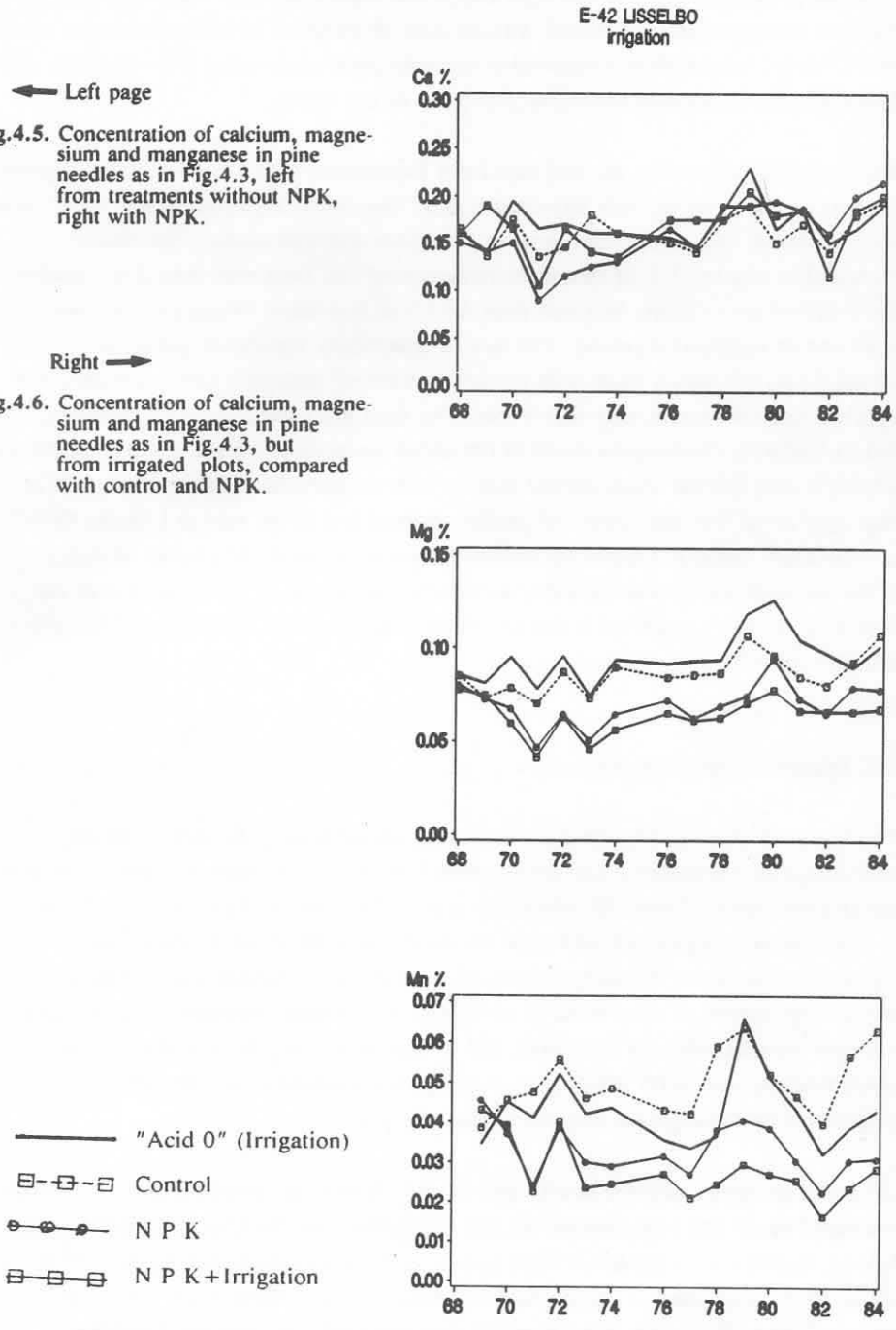

E-42 LISSELBO
without NPK
E-42 LISSELBO
with NPK
Ca %
Mg %
Mn %
"Ac 0"
Acid 1
Acid 2
Lime
NPK
Acid1+NPK
Acid2+NPK
Lime+NPK

← Left page

Fig.4.5. Concentration of calcium, magnesium and manganese in pine needles as in Fig.4.3, left from treatments without NPK, right with NPK.

Right →

Fig.4.6. Concentration of calcium, magnesium and manganese in pine needles as in Fig.4.3, but from irrigated plots, compared with control and NPK.



of the unfertilised plots) showed nitrification and higher nitrogen mineralisation than the corresponding treatments without lime. Both series of incubation experiments with Lisselbo humus show considerable variation between samples from duplicate plots, which may partly explain the inconclusiveness of the results.

As mentioned previously, the soil data from Experiment E 42 Lisselbo have not given as clear results as those from Experiment E 57 Norrliden. However, where trends have been observed, they agree with those at Norrliden and thus confirm the results discussed in Section 3.1. It should be remembered that treatment Acid 2 at Lisselbo has supplied only slightly less acid than Acid 3 at Norrliden, because of the two years longer application period. The lack of statistically significant results at Lisselbo has, of course, to do with the low number of replicates and treatments, but also real site differences may play a role. The sand at Lisselbo is very permeable, and in lysimeter experiments much of the added ammonium nitrate and part of the added sulphuric acid left the upper profile rapidly with the percolate (Tamm et al., 1977). This may mean that the upper soil profile retained less of the acid at Lisselbo than at Norrliden. There is a slight contradiction here with the slightly better recovery of the fertiliser nitrogen at Lisselbo, as reported above, so no firm conclusions can be drawn. In any case, there is the possibility that the effect of strong acid is different on soils with different textures.

4.2. Diagnostic needle analyses.

The results of the foliar analyses for nitrogen, phosphorus, potassium, calcium, magnesium and manganese are presented in Figs. 4.3 - 4.6. Figs. 4.3 and 4.5 deal with the element concentrations in relation to acid or lime applications (see legend) and to fertilisation (compare left and right diagrams). It is immediately clear that fertilisation raises the nitrogen concentrations, but other treatments (acidification and liming) appear to have small or no effects on the foliar nitrogen. Figs. 4.4 and 4.6 deal with the effect of irrigation, and it is evident from Fig. 4.4 that nitrogen concentrations are hardly affected by the irrigation treatment (but possibly magnesium and manganese concentrations, Fig.4.6).

On the other hand, addition of nitrogen tends to lower the concentrations of elements not supplied, in this case magnesium and manganese, by "biological dilution" (see below). Calcium concentrations were also lowered on fertilised plots from 1970 to about 1976, after which a certain recovery seems to have taken place, presumably because some calcium has been supplied with the fertilisers, and the difference in growth rate between fertilised and non-fertilised plots has decreased (section 4.3).

The amounts of phosphorus and potassium in the fertilisers seem to have more than compensated the "biological dilution" effect of the nitrogen. There is a considerable between-year variation in most nutrient concentrations already on unfertilised plots, but some of the P and K highs in the diagrams coincide with the application years. No clear pattern in the levels of these two elements can be observed in relation to the acid treatments even if the treatment curves (acid and lime) appear to end at slightly higher P and K levels than the "Acid 0" curve.

Liming has clearly increased the calcium levels in the needles, although the effect is moderate compared with what happens in some other tree species (Seibt & Wittich, 1965). On the other hand, manganese has decreased on limed plots, both fertilised and non-fertilised (sampling was discontinued on plots with Lime+NPK in 1979 due to strong growth disturbances on the plots, see below). The possibility cannot be excluded that acid applications have lowered concentrations of magnesium and calcium slightly, but similar differences occur between treatments "Acid 0" and Control (Fig.4.6) and might thus be accidental.

As a summary of the foliar analyses it can be stated that they confirm the great importance of nitrogen availability for needle element contents, not only for the nitrogen concentrations. Application of P and K raises the levels of these elements, as expected, which is also the case with calcium on limed plots. Manganese concentrations are depressed by liming. In the case of the acid applications, there are no very clear effects on the concentrations of the investigated elements. Whether this is due to absence of real effects, or to unfavourable "signal to noise" relations, can be discussed. Yet there is no contradiction with the Norrliden results (Fig. 3.13), where foliar magnesium concentrations tended to be depressed by acid application. A similar trend can be traced in the Lisselbo data (Fig. 4.5).

4.3. Tree growth.

The tree stand at Lisselbo was, on average, 2.4 m high at the start of the experiment in the spring of 1969, with a variation between plots from 2.1 to 2.8 m. The number of stems varied from 1100 to 1560 stems per hectare, with an average of 1320. Stand data are presented in the Appendix, Table 8.22, from the start (1969) and the first volume measurements in 1971, and from the most recent measurements in 1985. Data for basal area and volume growth are also given for the periods 1972-1977 and 1978-1985. The NPK + Lime treatment has been excluded, as the stand there soon showed serious dieback, due to deficiency in boron (Aronsson, 1980, 1983). One of the plots with

this treatment showed lower basal area than expected already in 1971 (Tamm et al., 1974), and the duplicate plot soon developed similarly, until the stand more or less collapsed on both plots.

The variation between plots, even within the same treatment, is considerable, as can be seen in Table 8.22. Two replications of each treatment are clearly too few to result in statistically significant evidence, unless the treatment effects are very large. The only treatment effects easily visible in Table 8.22 concern the differences between plots with or without NPK. Fertilised plots have consistently higher basal areas in 1985 than their unfertilised counterparts and similar differences occur in basal area and volume increments. In contrast, fertilised pines were, on average, four decimetres shorter than unfertilised ones in 1985.

Nonetheless we have the technique of adjustment for differences in start conditions by analysis of covariance as a help to at least visualise the tree growth trends. In spite of the low number of replicates, we have found a significant linear relationship between stand volume and the Bjørgung index (see Section 3.3). In experiment E 42 this index explains 93 per cent of the within-treatment variation in volume in 1971 and 67 per cent in 1985, with intermediary values for the years in between. Analysis of covariance with stem volume or volume growth as dependent variable has been used earlier (Aronsson & Tamm, 1982) on a data set from Expt.E 42 (concerning the effect of the irrigation treatment), in an attempt to eliminate some of the variation in stand condition by adjustment for differences in Bjørgung's index. In Expt. E 42 taken alone the effect of irrigation could not be statistically proven, as could hardly be expected with a relatively small effect in an experiment with only two duplicates. However, in a sign test including also three other similar experiments, the effect was significant (Aronsson & Tamm, 1982).

According to Section 3, the effects of acid application on tree growth were considerably smaller than those of fertilisation at Norrliden. At Lisselbo there are no statistically confirmed effects of acidification, but we have, for comparative purposes, made diagrams (Figs.4.8 and 4.9), constructed in the same way as Fig.3.19. Before we look at these diagrams showing relative growth, however, we have to consider the general growth pattern and the influence of the adjustment by Bjørgung's index in Fig. 4.7.

Fig.4.7 illustrates the general volume growth trends in control plots and the effect of fertilisation with regime N2P2K2 (Table 2.2). The first diagram, 4.7.A, shows the results obtained directly from the field measurements of diameter b h and tree height (the same as listed in the Appendix, Table 8.22). There is apparently an overlap

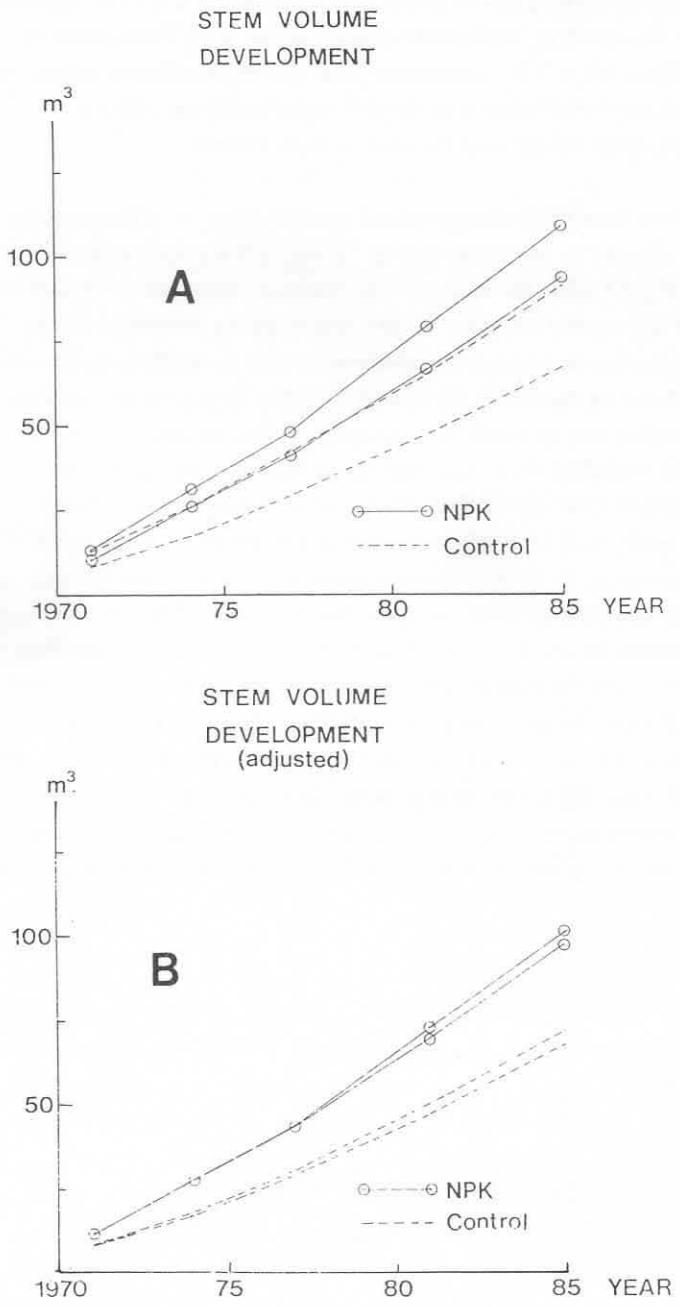


Fig.4.7. Stem volume development (over bark) of the individual plots of the treatments NPK and Control in Experiment **E 42. A** unadjusted, **B** adjusted for differences in initial conditions as measured by Bjørgung's index, computed from mean height and number of stems in 1968, as given in Table 8.22 (see text).

between the two treatments, although we know from experiment E 40 that there was a strong effect of NPK fertilisation, particularly during earlier years (Albrektson et al., 1977; Tamm, 1985). Fig.4.7.B, constructed from the index-adjusted values, has reduced the within-treatment variation considerably and a treatment effect is evident, amounting to about 40 per cent increase in stem volume.

In Figs. 4.8 and 4.9 we have used relative values (control mean = 100) as earlier in Fig.3.19 (all values adjusted as described above). In Fig. 4.9 the individual plot values are given, in Fig.4.8 only the means of the duplicate plots. The variation in the diagrams may be due to the following causes, where the experimental design prevents a strict distribution on causes: 1. Treatment effects. 2. Differences in initial plot conditions not expressed by the Bjørgung index. 3. Stochastic variation in control plot data giving rise to systematic variation in the treatment curves. 4. Stochastic variation in treatment data. In addition, we have to observe that the treatments were started in 1969 (1970 for Acid 1), which means that treatment effects, if occurring at all, have also influenced the stand growth for some years before the start of the curves in 1971. Concerning point 3 above, a possible lack of representativity of the two control plots, we have checked this by forming the ratios between observed volumes in the four control plots of Experiment E 40 and those in E 42, multiplied by 100 to get percentage units. The result is the very constant series of values (120 to 123) reproduced at the bottom of Fig. 4.9. Even if the E 40 control trees are, on average, 20 per cent larger than those of E 42, their growth rates are very similar, so point 3 should not be an important source of error, despite the textural differences mentioned in section 4.1. For point 4, some information can be obtained from the relatively moderate differences between similarly treated plots in Fig.4.9.

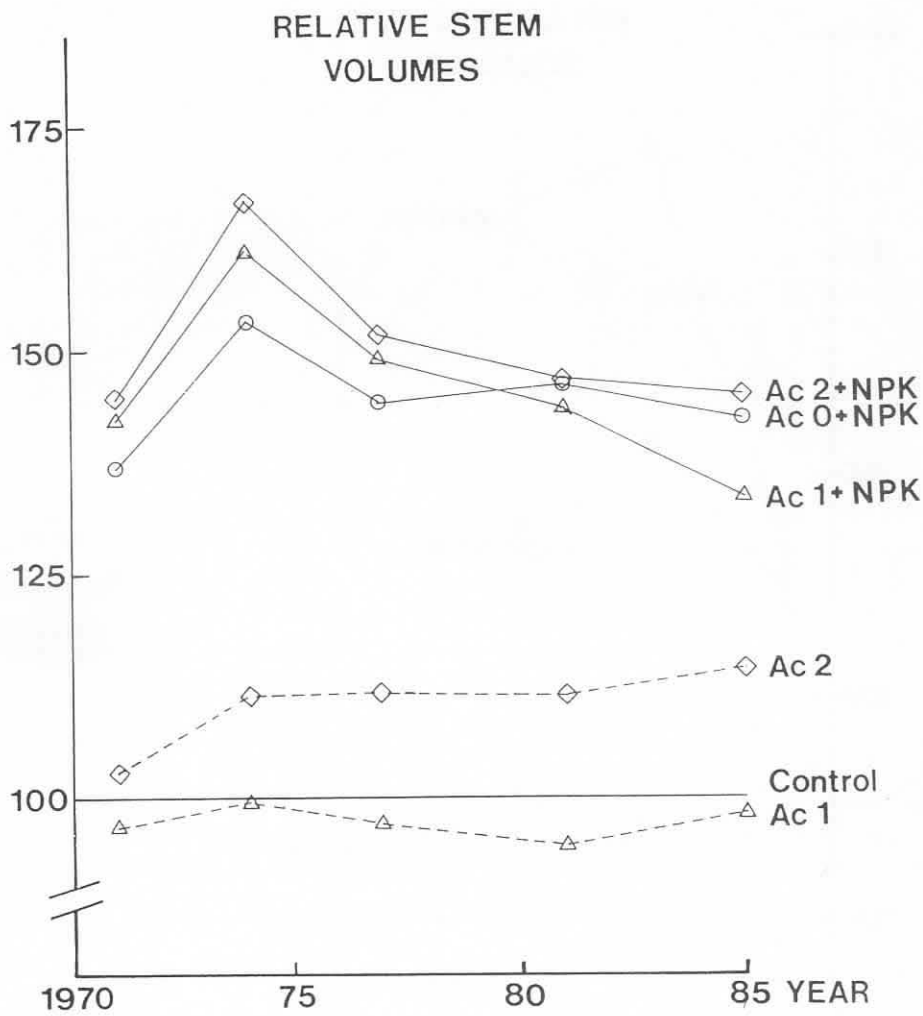


Fig. 4.8. Relative stem volumes over bark of the treatments in the acidification experiment E 42. Each value is the mean of duplicate plots, adjusted for differences in Bjørgung index. Control set to 100.

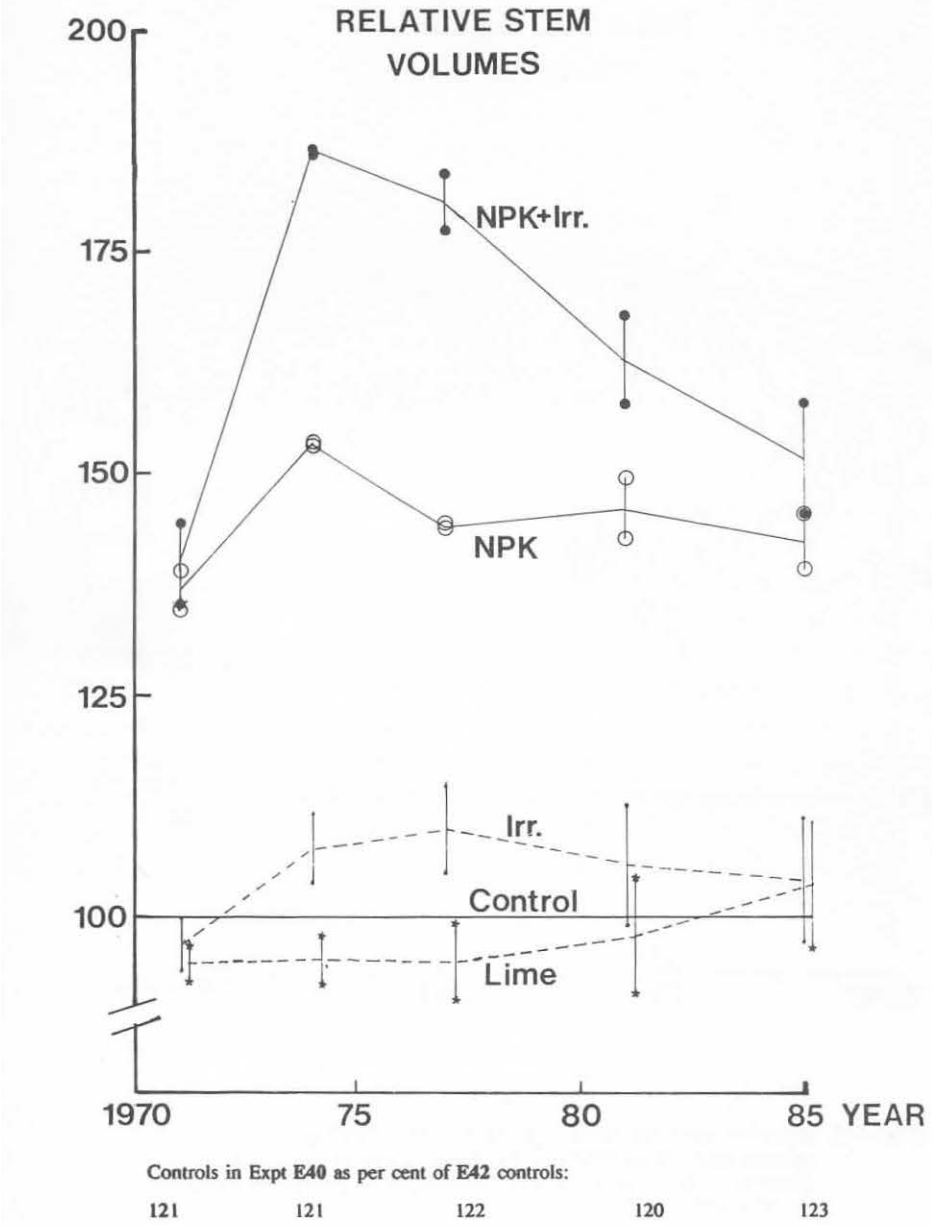


Fig. 4.9. Relative stem volumes over bark of the treatments with irrigation and liming in Experiment **E 42.** Individual plot values are joined by vertical lines; curves are drawn through treatment means. Control mean set to 100.
The figures below the x-axis are the ratios between the means of the controls in **Expt 40,** and the **E 42** control means, multiplied by 100. See text.

The trend differences between NPK + irrigation and NPK only in Fig.4.9, and the smaller but similar difference between irrigation and control during the period 1971-1977, are probably due to a treatment reaction, which, however, is followed by a period of convergence. If we accept that there has been a positive reaction to irrigation (cf. Aronsson & Tamm, 1981), we can also say that this effect has been temporary, and that tree growth during the last measuring period has hardly been affected by the irrigation to any measurable extent. It is not very likely that the trees have made themselves less dependent on irrigation by reaching the capillary zone with their roots, as three of four irrigated plots (and both controls) are located on the upper slope or top of the esker.

The conclusion of small and only temporary effects of irrigation provides some support to our use of irrigated plots as substitutes of controls in the 1985 soil sampling. A similar temporary irrigation response has been obtained in Experiment E 58 at Norrliden (Tamm et al., in prep.).

From Fig.4.8 we may conclude that any effects on tree growth of the experimental acidification have been small. If we accept that treatment Acid 1 has had very little effect on the soil (section 4.1), it is mainly the treatments Acid 2 and NPK + Acid 2 which are of interest. The curve for Acid 2 shows a slightly upward trend, as at Norrliden. On the other hand, treatment NPK + Acid 2 follows the NPK curve, although it started from a higher value. There is, thus, no very clear negative effect of NPK + Acid 2 at Lisselbo, comparable to that found at Norrliden with both NPK + Acid 2 and NPK + Acid 3. The curve for NPK + Acid 1 shows a negative trend, but with the lack of evidence that there was an effect of this treatment on the soil this may be purely accidental.

As field measurements of tree growth is a crude method, the lack of clear results is understandable. As boring for increment cores has not been possible so far because of the small dimensions of the trees, we cannot get further in our interpretation of the Lisselbo results. Yet it might be worthwhile to sample increment cores or stem sections in the future. Cores have already been collected from trees felled (or overturned) because of snow-damage in the winter of 1988-1989.

4.4. Vegetation changes.

In the first years there was little effect of the treatments, including acid application, on the field layer vegetation at Lisselbo, where heather, Calluna vulgaris, was the dominating dwarf shrub. However, the bottom layer of mosses and (mostly) reindeer lichens suffered from both acid, lime and NPK. Combinations of two treatments damaged more than the single treatments. The damage by acid on the field layer increased with time, while there has been a considerable recovery since the last application in 1976. NPK fertilisation has favoured the grass Deschampsia flexuosa and the herb Epilobium angustifolium at the expense of the original dwarf shrubs. The natural succession leads to a replacement of Calluna by Vaccinium vitis idea and V. myrtillus with increasing shade from the canopy.

A detailed study of the vegetation on the whole experimental area has been carried out recently (1987) by Dirkse (in prep.), showing, i.a., that nitrogen fertilisation is the treatment with the most profound influence, with Deschampsia flexuosa and Epilobium angustifolium as favoured species. Also acidification has had an influence, most evident for some of the mosses. Pohlia nutans was favoured by acidification, while Pleurozium schreberi behaved in the opposite way.

Inventories of fungal fruiting bodies have been made by Wästerlund (1982) and more recently by Gahne (in prep.). Both acid and NPK have decreased the frequency of fruiting bodies of mycorrhizal fungi, with the exception of Lactarius rufus, which was favoured by acidification.

4.5. Discussion.

The Lisselbo acidification plots have already been described as a pilot study, to our knowledge being the first regular attempt to test in field experiments the hypothesis presented in 1968 by Odén about site deterioration due to acid deposition. The number of replicates and also of levels of acid application was small, and could give conclusive answers only if the effects were strong. Yet it may be worthwhile to compare the experiences and tendencies from the Lisselbo experiment with those from Norrliden.

The analyses of the humus layer and the upper mineral soil in 1971 and 1976 seemed to indicate that the acidified plots had lower base saturation and slightly lower pH values than their counterparts without acidification (Acid plots compared with control and irrigation plots, Acid + NPK plots compared with NPK and NPK+Irrigation plots). In 1985 this difference had disappeared in the humus layer and was very small in the upper mineral soil. The detailed examination of the different exchangeable cations often revealed slightly lower values on acidified plots, but the differences were not fully consistent.

The treatments NPK and Lime, alone or in combination with other treatments, affected soil properties more than the application of acid. As has been discussed in section 3.1, NPK tends to decrease the pH of the mineral soil (but not the humus layer) while it increases base saturation. Liming increases pH in both humus and mineral soil and stimulates nitrification in incubation experiments, especially in combination with fertilisation. No effects of the irrigation have been found in the soil analyses, even if Farrell et al.(1980) found small deviations in acid-base status between irrigated and control lysimeters, treated in the same way as the plots.

The tree growth measurements reveal no statistically significant effect of the acid treatments, even if a slight positive influence of at least the Acid 2 treatment cannot be excluded. NPK fertiliser has increased stem diameter growth and branch growth (but not height growth), as is also the case in Experiment E40 at Lisselbo (Tamm et al., in prep.). Irrigation, especially when combined with fertilisation, appears to have increased stem volume growth, while lime alone had little or no effect (Lime with NPK had a disastrous effect by inducing deficiency in boron).

In summary: Although most growth results and chemical data from the Lisselbo pilot experiment lack statistical significance it seems clear that the ecosystem has been able to receive considerable amounts of acid without strong effects persisting in the upper soil horizons and the tree stand. According to lysimeter studies (Farrell et al., 1980) running parallel to the plot experiment 40 - 60 per cent of the added sulphate was lost during the experimental period from the top soil. This means that also base cations were lost from the exchangeable pool, but there seems to have been a compensation for these losses, presumably both by weathering of primary minerals and by changes in colloids, possibly also by root uptake from deeper horizons.

5. CONCLUSIONS

Although the two experiments described in this paper, E 57 Norrliden and E 42 Lisselbo, have similar treatments, it is mainly from the Norrliden experiment that we can draw fully reliable conclusions. The reason for this may be the low number of replicates and levels of acid in the Lisselbo experiment, but possibly also that this site is less sensitive to application of sulphuric acid than Norrliden, as some of the applied acid might have percolated more rapidly on the well to excessively drained site with a coarse textured sandy soil.

On both sites the acid application damaged the existing vegetation, particularly when given with NPK fertiliser. The stands of young Scots pine appeared totally unharmed by the acid treatment (as well as by liming without NPK). NPK fertiliser increased needle production, branch growth and basal area growth but not height growth. NPK addition also led to increase in some vegetation components, particularly Deschampsia flexuosa and Epilobium angustifolium where stand density permitted, instead of the original dwarf shrubs, mosses and lichens. NPK + Lime decreased needle boron concentrations more than other treatments and caused severe dieback of the pine at Lisselbo.

Since the acid applications ended in 1976 (while fertilisation continued, annually with ammonium nitrate), a certain vegetation recovery has occurred on non-fertilised plots, while the acidified and fertilised plots developed much as those fertilised only.

The acid application, particularly at higher levels, did acidify the humus layer and the uppermost mineral soil during the treatment, but nine years after the last acid application there was little left of the effect on the humus layer at either site, but the mineral soil (0 - 20 cm) had been significantly acidified at Norrliden and there is a tendency in the same direction at Lisselbo for the Acid 2 treatment, the highest level given there. Besides changes in pH and base saturation, there had been significant losses of magnesium and calcium from the soil profile. We consider the downward transport of sulphate ions, removing basic cations such as calcium and magnesium from the rooting zone, as the key process in the soil acidification by added sulphuric acid (the "mobile anion" concept, Seip, 1980).

NPK addition led to a pH increase in the humus layer at Norrliden, but acidified the mineral soil much more than the application of sulphuric acid. It should then,

however, be remembered that the amounts of acid or acidifying substances were much higher with NPK than with sulphuric acid, if expressed as moles of charge. We explain the acidification from NPK, (presumably mostly from the nitrate component of the fertiliser) as an effect of adding "mobile anions" to a soil with a high amount (and production) of protons in the humus layer. Nitrification can not be entirely ruled out as a cause of acidification, but incubation experiments with humus from both sites on different occasions have shown a considerable disinclination to nitrification even in samples from fertilised plots, except after liming.

As already stated, NPK addition increased tree growth on both sites. In addition, there was a small but statistically significant positive response to acid in tree growth at Norrliden on unfertilised plots, described by a straight line for the stem volume measurements but by an "optimum curve" for the more accurate basal area measurements. With fertiliser, both types of measurements showed a negative response to acid, statistically significant for basal area. At Lisselbo a positive growth trend also occurred for the Acid 2 treatment without fertiliser. Studies of the time development of the growth reactions indicate that the observed positive responses occurred during the acid treatment period, while the negative responses (with fertiliser) started after a few years and increased even after the acid treatment period.

Our tentative explanation of the positive response to acid is decreased competition from other vegetation but also (and probably more important) from microorganisms. This hypothesis is supported by several observations of decreased microbiological activity on acidified plots and in laboratory studies on samples from these plots (Popovic, 1984; Bååth et al., 1980; Persson et al., 1989).

Field experiments with soil acidification to forest plots have been done also in Norway, as mentioned earlier. Temporary positive effects, followed by a negative after-reaction, were reported by Abrahamsen et al. (1983) and Abrahamsen (1984) from an experiment in a young pine stand. A delayed negative effect of acidification of a spruce stand has been reported by Stuanes et al.(1988). These experiments used a more sophisticated technique than ours, although the Norwegian authors also warn about possible artifacts from irrigation with water adjusted to pH 2.5 and 3. Yet the Norwegian results do not contradict those presented here with respect to effects on soils and trees. Instead, information from the Norwegian and Swedish experiments is complementary, with i.e. the interaction acid/lime being studied in Norway and acid/fertilizer in Sweden.

As stated in the introduction, our experiments started as rather crude pilot experiments, the first one (Lisselbo) on a small scale with respect to number of replicates and treatments. Adding fairly strong mineral acid to a forest soil might easily produce artifacts. Certainly some organisms were killed; ground vegetation by direct spraying, some soil organisms such as enchytraeids by extreme acidity or other chemical effects. It is a recurrent dilemma in experimentation with slow-acting environmental factors that there are risks for artifacts in all attempts to imitate in a short time-span processes taking decades or more on natural sites. Even in the careful Norwegian experiments where acidity-adjusted water was used, some effects occurred on vegetation and biota similar to those observed by us. Also some of the effects of conventional forest fertilisation on soil biota have been ascribed to artifacts, such as high salt concentrations in the soil solution (Heugens, 1984; Huhta et al., 1986). Our approach, since the Lisselbo experiment had shown that the trees could stand the acid treatments without apparent damage, has been to concentrate the acid applications to a limited period, and then to study after-effects. In some other experiments we have tested elementary sulphur as acidifying agent (Tamm & Popovic, in prep.); this avoids osmotic effects and also extremely high acidity, but does not exclude selective effects on organisms. We feel that the moderate effect of acid on the trees, especially during the period after termination of application, together with the gradual recovery of vegetation on acidified plots (original constituents on plots with acid only, nitrophilous species on plots with additional fertilisation), supports our view that the observed growth effects in later years are true effects of soil changes, not short-term artifacts. This applies in particular to the negative interaction acid x fertiliser and to the somewhat less well documented negative effect of the highest level of acid. We have not compared the effects of dilute, but still strong, sulphuric acid with the Norwegian approach of adding large amounts of water, adjusted to predetermined pH values. Common sense suggests that the risks for artifacts would be higher in our approach, but as such reactions (increased weathering, reactions with proteins in living organisms) consume protons, they may decrease long-term effects. The rapid leaching of sulphate in the Lisselbo lysimeter experiments has already been mentioned.

The negative interaction between applications of acid and fertilisers is in contrast to our original hypothesis at the start of the experiment, viz. that fertilisation should counteract possible negative effects of acid deposition. A simple explanation might be the strong acidification of the mineral soil by the fertiliser (mainly by the nitrogen component, Tamm, 1989), which adds to the negative effect of the highest acid level, as observed in the basal area measurements.

As the present deposition situation in large parts of Europe means deposition of acidifying compounds of both sulphur and nitrogen, the negative interaction just discussed is probably more relevant for discussions of negative loads than the effects of application of acid only. Apparently the "critical load" (Nilsson & Grennfelt, 1988.) for sulphur applied alone at Norrliden (and presumably Lisselbo) is at or above the amount given with Acid 2 (about 200 kg S per hectare), and almost certainly below Acid 3, even if different measuring methods give different results. But when also ammonium nitrate is given (in large amounts), the "critical load" for a well functioning pine ecosystem seems to be exceeded even with Acid 2. The "critical load" for nitrogen given alone or with PK but without sulphuric acid can not be decided from experiments E 57 and E 42, but this question will be addressed in a paper dealing with other experiments at Norrliden and Lisselbo (Tamm et al., in prep.)

6. ACKNOWLEDGEMENTS

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During the long period from 1968, when the Lisselbo site was selected, to 1989, when this report has been compiled and edited, many collaborators within the former Section of Forest Ecology at the Royal College of Forestry and the present Section of Forest Ecology at Department of Ecology and Environmental Research of the Swedish University of Agricultural Sciences have helped to maintain the experiments and to evaluate the results. Also many colleagues outside the Forest Ecology Section have contributed significantly. It is not possible here to thank all persons involved, but the following names must be mentioned.

The planning of the experiments was discussed with Professor Bertil Matern, who also helped with early statistical evaluations, and with the late Professor Svante Oden, who also took part in the first studies of the soil effects of the acid applications.

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REFERENCES

Abrahamsen,G., Stuanes,A.O. and Tveite,B. 1983: Effects of long range transported air pollutants in Scandinavia.- Water Quality Bull.8,89-95.

Abrahamsen,G. 1984: Effects of acidic deposition on forest soil and vegetation - Phil. Trans. R. Soc. London, B.305, 369-382.

Albrektsson,A., Aronsson,A. and Tamm,C.O. 1977: The effect of forest fertilization on primary production and nutrient cycling in the forest ecosystem - Silva Fennica, 11(3), 233-239.

Andersson,S.O. 1954: Funktioner och tabeller för kubering av småträd.- Medd. Stat. Skogsforskn. Inst. 44, 12, 1-29.

Anonymous. 1986: Sura och försurade vatten - Monitor 1986. Liber, Stockholm.

Aronsson,A., 1980: Frost hardiness in Scots pine(Pinus sylvestris L.) II. Hardiness during winter and spring in young trees with different mineral nutrient status.- Stud. For. Suec. 155, 1-27.

Aronsson,A., 1983: Growth disturbances caused by boron deficiency in some fertilized pine and spruce stands on mineral soils.- Comm. Inst. For. Fenn. 116, 116-122.

Aronsson,A. and Tamm,C.O. 1982: Effects of irrigation on young stands of pine (Pinus sylvestris L.) and spruce (Picea abies Karst.).-In: Bo Ranneby (ed.), Statistics in theory and practice. Essays in honour of Bertil Matérn. Umeå, 53-69.

Balsberg,A-M.(ed.) 1975: Handledning i kemiska metoder vid växtekologiska arbeten.- Medd. Avd. Ekol. Bot. Lunds Univ. Årg.3, nr 2, 1-93.

Bjørgung,E. 1968: Om kovariansanalyse av volum i gjødslingsforsøk.- Norsk Skogbruk. 9, 229-231.

Bremner,J.M. and Douglas,L.A. 1971: Use of plastic film for aeration in soil incubation experiments.- Soil Biol.Biochem., 3, 289-296.

Bååth,E., Berg,B., Lohm,U., Lundgren,B., Lundkvist,H., Rosswall,T., Söderström,B. and Wirén,A. 1980: Effects of experimental acidification on soil organisms and decomposition in a Scots pine forest.- Pedobiologia 20, 85-100.

Bååth,E., Lundgren, B. and Söderström, B. 1984: Fungal populations in podzolic soil experimentally acidified to simulate acid rain. - Microb. Ecol. 10, 197-203.

Dahl,E. and Skre,O., 1971: An investigation of the effect of acid precipitation on land productivity. (In Norwegian.) - Konferens om avsvavling. Stockholm 11.nov.1969. Nordforsk. Miljövårdsekr, publ. 1, 27-39.

Derome,J., Kukkola,M., and Mälkönen,E. 1986: Forest liming on mineral soils. Results of Finnish experiments.- SNV PM 3084, pp 1-107.

Dirkse,G.M. and van Dobben,H.P. 1989: Effects of experimental fertilisation on forest undergrowth in young stands of scots pine in Sweden. In: Sjögren E. (ed.):

Forests of the world: diversity and dynamics (Abstracts). Studies in Plant Ecology, 18, 62-65.

FAO-UNESCO, 1985: Soil map of the world. Revised legend. FAO, Rome.

Falck,J., 1973: En metod för bestämning av humusskiktets innehåll av växtnäringsämnen. - Dept. Silviculture, Royal Coll. For. Stockholm. Res.Note No 1, 129 pp.

Farrell,E.P., Nilsson,S.I., Tamm,C.O., and Wiklander,G. 1980: Effects of artificial acidification with sulphuric acid on soil chemistry in a Scots pine forest.- In: D.Drabløs and A.Tollan (Eds.),Ecological Impact of Acid Precipitation. Proc. Int. Conf. Sandefjord, 11-14 March 1980, SNSF Project, NISK, Ås, Norway, pp 186-187.

Farrell,E.P., Nilsson,S.I., Wiklander,G. and Tamm,C.O. 1984: Distribution of sulphur fractions in lysimeters previously treated with sulphuric acid, NPK fertilizer and a combination of acid and fertilizer.- Forest Ecology and Management 8, 41-57.

Hallbäcken,L., and Popovic,B. 1985: Markkemiska effekter av skogsmarkskalkning. Revision av skogliga kalkningsförsök.- SNV PM 1880.

Heugens, A. 1984: The influence of some acids, bases and salts on an enchytraeid population of a pine litter substrate.- Pedobiologia 26,137-141.

Heugens, A., and van Daele, E. 1984: The influence of some acids, bases and salts on the mite and Collembola population of a pine litter substrate.- Pedobiologia 27, 299-311.

Hesselman,H. 1937: Om humustäckets beroende av beståndets ålder och sammansättning i den nordiska granskogen av blåbärsrik Vaccinium typ och dess inverkan på skogens föryngring och tillväxt. - Medd. Stat. Skogsförs.anst. 30, 529-715.

Holmen,H., Nilson,Å., Popovic,B. and Wiklander,G., 1976: The optimum nutrition experiment Norrliden. A brief description of an experiment in a young stand of Scots pine.- Department of Forest Ecology and Forest Soils, Royal College of Forestry, Stockholm,Res.Notes No 26, 1-34.

Huhta,V., Hyvönen,R., Koskenniemi,A., Vilkamaa,P., Kaasalainen, P., and Sulander,M. 1986: Response of soil fauna to fertilization and manipulation of pH in coniferous forests.- Acta Forestalia Fennica, 195, 1-30.

Högberg,P., Granström,A., Johansson,T., Lundmark-Thelin,A. and Näsholm,T. 1986: Plant nitrate reductase activity as an indicator of availibility of nitrate in forest soils.- Can. J. For. Res, 16, 1165-1169.

Ingestad,T. 1958: Studies on manganese deficiency in a forest stand.- Medd. Stat. Skogsforsk. inst. 48(4), 1-20.

Ingestad,T. 1962: Macro element nutrition of pine, spruce and birch seedlings in nutrient solutions. - Medd.Stat.Skogsforsk.inst. 51(7), 1-131.

Ingestad,T. 1982: Relative addition rate and external concentration. Driving variables used in plant nutrition research.- Plant Cell and Environment, 5, 443-453.

Ingestad,T., and Kähr,M., 1985: Nutrition and growth of coniferous seedlings at varied relative nitrogen addition rate.- Physiol. Plant. 65, 109-116.

Lohm,U., Larsson,K. and Nömmik,H. 1984: Acidification and liming of coniferous forest soil: long-term effects on turnover rates of carbon and nitrogen during an incubation experiment.- Soil Biol. Biochem. 16, 343-346.

Näslund,M. 1940-41: Funktioner och tabeller för kubering av stående träd. Tall, gran och björk i norra Sverige.- Medd. Stat. Skogsforskn. Inst. 32, 87-141.

Näslund,M. 1947: Funktioner och tabeller för kubering av stående träd. Tall, gran och björk i södra Sverige samt i hela landet. - Medd. Stat. Skogsforskn. Inst. 36, 1-81.

Nilsson,J. and Grennfelt,P. 1988 (eds.) Critical loads for sulphur and nitrogen. - Report from a workshop held at Skokloster, Sweden 19-24 March 1988, UN-ECE and Nordic Counc. of Ministers. Miljörapport 1988:15, 418 p.

Nömmik,H. 1971: A technique for determining mineralization of carbon in soil during incubation.- Soil Science 112, 131-136.

Nömmik,H. 1974: Ammonium chloride-imidazole extraction procedure for determining titratable acidity, exchangeable base cations and cations exchange capacity in soils. - Soil Science 118, 254-262.

Odén,S. 1968: Nederbördens och luftens försurning, dess orsaker, förlopp och verkan i olika miljöer.- Ecol .Comm. Bulletin, Stockholm, No.1.

Persson,T. 1988: Effects of acidification and liming on soil biology. - In: Andersson,F. and Persson,T.(Ed.), Liming as a measure to improve soil and tree condition in areas affected by air pollution. SNV Report 3518, 53-70.

Persson,T., Wirén,A., Andersson,S. and Gahne,B. 1989: Markbiologiska effekter av skogsgödsling. - (Kungl. Skogs- och Lantbruksakad. Tidskr. Suppl. Stockholm, in press).

Popovic,B. 1971: Effect of sampling date on nitrogen mobilisation during incubation experiments.- Plant and Soil, 34, No 2, 381-391.

Popovic,B. 1977: Effect of ammonium nitrate and urea fertilizers on nitrogen mineralization, especially nitrification, in a forest soil.- Dept. of Forest Ecol. and Forest Soils. Stockholm. Res.Notes No 30, 1-26.

Popovic,B. 1984: Mineralization of carbon and nitrogen in humus from field acidification studies. - Forest Ecol. and Managem., 8. 81-93.

Romell,L.G. 1935: Ecological problems of the humus layer in the forest. - Cornell Univ. Agric. Expt. Sta. Memo. 170, 1-28.

Romell,L.G. 1967: Die Reutbetribe und ihr Geheimnis.- Studium generale, Bd.20 (6), 362-369.

Seibt,G. and Wittich,W. 1965: Ergebnisse langfristiger Düngungsversuche im Gebiet des nordwestdeutschen Diluviums und ihre Folgerungen für die Praxis.- Schriftenreihe der Forstl.Fak.der Univ.Göttingen, Band 27/28.1-156.

Seip,H.M., 1980: Acidification of freshwater - sources and mechanisms. - In: Drabløs, D. and Tollan, A. (eds.): Ecological impact of acid precipitation, 358-365, SNSF-project.

Selmer-Olsen,A.R. 1971: Determination of ammonium in soil extract by an automated indophenol method. - Analyst 16, 565-568.

Sinclaire,A.G. 1972: An 'AutoAnalyzer' method for determination of extractable sulphate in soil.- N. Z. J. of Agric. Res. 16, 287-292.

Stuanes,A.O., Abrahamsen.G., and Tveite,B 1988: Effect of artificial rain on soil chemical properties and forest growth. - In: Air Pollution and Ecosystems. Mathy, P.(ed.). Proc. Int. Symp. Grenoble, France, 18-22 May, 1987.Dordrecht,pp 248-253.

Talme,O. & Almén,K-E. 1975: Jordartsanalys. Laboratorieövningar. - Kvartärgeologiska Institutionen, Sthlms Universitet, Del 1.

Tamm, C.O. 1956: Studier över skogens näringsförhållanden. III. Försök med tillförsel av växtnäringsämnen till ett skogsbestånd på mager sandmark.- Medd. Stat. Skogsforsk. Inst.46, 1-84.

Tamm, C.O. 1964: Determination of nutrient requirements of forest stands.- Int. Rev. For. Res. 1, 115-170.

Tamm,C.O. 1976: Acid precipitation: biological effects in soil and on forest vegetation.- AMBIO 5, 235-238..

Tamm,C.O. 1985: De skogliga bördighetsförsöken.- Mål, metoder, tillväxt resultat. (The Swedish optimum experiments in forest stands.- Aims, methods, yield results.) Kungl.Skogs- och Lantbruksakad. Tidskr. Suppl. 17, 9-29.

Tamm, C.O. 1989. The importance of field experiments in the study of soil-mediated effects of air pollution on forests. - Medd. Norsk inst.f.skogforskning 42(1) (in press).

Tamm,C.O., Nilsson,Å. and Wiklander,G. 1974: The optimum nutrition experiment Lisselbo. A brief description of an experiment in a young stand of Scots pine.(Pinus sylvestris L.). - Dept. of Forest Ecol. and Forest Soils, Res.Notes No 18, 1-25.

Tamm,C.O., Wiklander,G. and Popovic,B. 1977: Effects of application of sulphuric acid to poor pine forests.- Water, Air and Soil Poll. 8, 75-87.

Tamm,C.O., and Wiklander G., 1980: Effects of artificial acidification with sulphuric acid on tree growth in Scots pine forest. In: D.Drabløs and A. Tollan (Eds.), Ecological Impact of Acid Precipitation. Proc. Int. Conf.,Sandefjord, Norway. SNSF Project, NISK, Ås, 188-189.

Tamm,C.O., Aronsson,A. and Popovic,B. 1984: Is field experimentation a relevant method to study the effects of changes in chemical climate on forest ecosystems.- In: Ågren,G.I.(ed.). State and change of forest ecosystems - Indicators in current research. Swed. Univ. Agric. Sci.,Dept Ecology and Environmental Research, Rep. 13. 251-259.

Tamm,C.O. and Hallbäcken,L., 1988: Changes in Soil Acidity in Two Forest Areas With Different Acid Deposition: 1920 to 1980s.- AMBIO 17, 56-61.

Tamm,O. 1934: En snabb metod för mineralogisk jordartgranskning.(Eine Schnellmethode für mineralogische Bodenuntersuchung).- Svenska Skogsvårdför. Tidskr. 32, 231-250.

Tamm,O. 1937: Om de lågproduktiva sandmarkerna å Hökensås och i övre Lagadalen. Über die schwachproduktiven Sandböden auf dem Hökensås und im oberem Lagatal, Südschweden).- Medd. Stat. Skogsforsk. Inst. 30, 1-66.

Tveite,B. 1980: Effects of acid precipitation on soil and forest. 9. Tree growth in field experiments. - In: Drabløs,D. & Tollan,A.(ed.), Ecol. Impact of Acid Prec., Proc. Int. Conf., Sandefjord, Norway, SNSF project, NISK, Ås, 206-207.

Walter,H. and Lieth,H. 1967: Klimadiagram - Weltatlas. Lief. 1-3, Fischer Verlag, Jena.

Van den Driessche,R., 1974: Prediction of mineral nutrient status of trees by foliar analysis.- Bot. Rev. 40, 347-394.

Waring,R. & Youngberg,C.T., 1972: Evaluating forest sites for potential growth response of trees to fertilizer.- Northwest Sci. 46, 67-75.

Viro,P.J. 1952: On the determination of stoniness.- Comm. Inst. For. Fenn., 40/3, 1-19.

Wästerlund,I. 1982: Försvinner tallens mykorrhizasvampar vid gödsling? (Do pine mycorrhizae disappear following fertilization?) - Svensk. Bot. Tidskr.76, 411-417.

APPENDIX

Table 8.1. Expt E57, Norrliden, Stoniness index, Si_{30cm} at different plots, each value is the mean of 25 measurements per plot, taken in 1977. Depth of the A_2 horizon (cm) at the different plots. Each value is the mean of 30 measurements per plot, taken in 1979.

	Treatment									
	- N P K					+ N P K				
Block	Ac 0	Ac 1	Ac 2	Ac 3	Lime	Ac 0	Ac 1	Ac 2	Ac 3	Lime
	Plot number									
13	6	1	3	5	8	7	10	4	2	9
12	16	20	13	19	17	15	18	12	11	14
11	23	25	22	27	30	29	21	24	26	28
	Stoniness index, Si_{30cm}									
13	24.9	25.8	23.4	26.5	26.6	27.7	29.4	22.9	22.6	25.5
12	25.5	23.6	27.1	24.2	25.9	25.3	28.0	25.5	26.5	25.3
11	24.1	28.6	21.4	20.2	24.8	21.3	27.3	24.5	26.0	24.2
Average	24.8	26.0	24.0	23.6	25.8	24.8	28.2	24.3	25.0	25.0
	Depth of A_2 horizon, cm									
13	8.8	8.7	9.1	7.8	8.8	8.2	9.3	8.3	8.2	9.1
12	8.4	8.6	9.3	9.5	9.1	10.8	6.9	8.6	8.0	9.2
11	9.1	9.3	8.7	8.9	9.6	10.0	10.5	9.5	8.4	9.8
Average	8.8	8.9	9.0	8.7	9.2	9.7	8.9	8.8	8.2	9.4

Table 8.2. Expt E57, Norrliden, pH-values and degree of base saturation (V%) in soil layers from differently treated plots. Sampling in June 1985. Means of three replicate plots. For significance tests (acid, lime and NPK effects, and interactions), see Table 3.2.

	Treatment									
	- N P K					+ N P K				
Soil layer	Acid 0	Acid 1	Acid 2	Acid 3	Lime	Acid 0	Acid 1	Acid 2	Acid 3	Lime
	pH-values									
Humus	4.3	4.2	4.2	4.2	6.9	4.7	4.5	4.6	4.5	6.1
Mineral soil										
0 - 5 cm	4.5	4.5	4.3	4.1	5.6	4.3	4.2	4.3	4.2	5.1
5 - 10 "	5.0	4.9	4.8	4.7	5.4	4.5	4.5	4.4	4.4	5.0
10 - 20 "	5.4	5.2	5.3	5.1	5.6	4.9	4.8	4.6	4.7	5.2
	Degree of base saturation (%)									
Humus	23.7	22.0	21.2	19.3	100.0	30.7	24.2	26.7	26.1	86.8
Mineral soil										
0 - 5 cm	21.6	17.1	14.2	9.7	74.4	19.4	19.3	21.5	15.4	57.2
5 - 10 "	17.7	11.9	14.9	7.9	32.8	12.6	11.2	9.2	9.2	25.4
10 - 20 "	20.0	16.0	15.5	11.3	29.9	15.6	12.7	8.9	11.0	27.3

Table 8.3. Expt E57, Norrliden, cation exchange capacity (CEC µeq/g d.w.) and titratable acidity (H µeq/g d.w.) in soil layers from differently treated plots. Sampling in June 1985. Means of three replicate plots. For significance tests (acid,lime and NPK effects, and interactions), see Table 3.2.

	Treatment									
	− N P K					+ N P K				
Soil layer	Acid 0	Acid 1	Acid 2	Acid 3	Lime	Acid 0	Acid 1	Acid 2	Acid 3	Lime
	Cation exchange capacity CEC µeq/g d.w.									
Humus	375	427	557	415	587	395	438	382	432	584
Mineral soil										
0 - 5 cm	50	49	48	57	70	65	55	54	59	71
5 - 10 "	45	42	44	45	45	57	49	62	54	54
10 - 20 "	25	22	34	28	20	29	31	39	29	27
	Titratable acidity H µeq/g d.w.									
Humus	286	333	439	331	0	273	335	279	325	78
Mineral soil										
0 - 5 cm	40	41	41	51	18	53	45	42	50	31
5 - 10 "	37	37	38	42	30	50	44	56	49	41
10 - 20 "	20	18	29	24	14	24	27	36	26	20

Table 8.4. Expt E57 , Norrliden, exchangeable calcium (Ca µeq/g d.w.) , exchangeable magnesium (Mg µeq/g d.w.) and exchangeable potassium (K µeq/g d.w.) in soil layers from differently treated plots. Sampling in June 1985. Means of three replicate plots. For significance tests (acid,lime and NPK effects, and interactions), see Table 3.2

Soil layer	Treatment									
			- N P K					+ N P K		
	Acid 0	Acid 1	Acid 2	Acid 3	Lime	Acid 0	Acid 1	Acid 2	Acid 3	Lime
	Exchangeable calcium Ca µeq/g d.w.									
Humus	69.5	72.8	92.2	69.0	566.9	106.2	84.6	87.3	91.4	481.1
Mineral soil										
0 - 5 cm	8.1	5.7	4.3	3.4	48.9	8.7	7.1	7.2	5.4	36.6
5 -10 "	6.0	3.4	4.3	2.0	12.7	4.4	2.8	2.6	2.5	11.0
10 -20 "	3.3	2.2	3.0	1.9	4.5	2.5	1.9	1.3	1.5	5.5
	Exchangeable magnesium Mg µeq/g d.w.									
Humus	11.6	13.0	15.8	8.2	12.1	8.3	10.2	7.6	7.1	11.8
Mineral soil										
0 - 5 cm	1.12	0.93	0.57	0.68	1.61	0.79	0.71	0.77	0.62	0.99
5 -10 "	0.85	0.50	0.51	0.34	0.78	0.33	0.32	0.38	0.28	0.38
10 -20 "	0.49	0.29	0.27	0.24	0.36	0.20	0.18	0.18	0.16	0.21
	Exchangeable potassium K µeq/g d.w.									
Humus	7.17	7.49	9.31	5.89	7.17	6.57	7.82	7.03	7.93	9.85
Mineral soil										
0 - 5 cm	1.31	1.29	1.37	1.11	1.38	2.70	2.78	3.29	2.84	2.22
5 -10 cm	0.99	0.98	1.61	0.97	1.12	2.28	2.24	2.43	2.05	2.20
10 -20 "	0.91	0.73	1.25	0.71	0.80	1.59	1.66	1.67	1.31	1.69

Table 8.5 Expt E57,Norrliden, exchangeable aluminium (Al_{KCl} µg/g d.w.) and extractable sulphate (S µg/g d.w.) in soil layers from differently treated plots. Sampling in June 1985. Means of three replicate plots. For significance tests (acid,lime and NPK effects, and interactions), see Table 3.2.

Soil layer	Treatment									
	- N P K					+ N P K				
	Acid 0	Acid 1	Acid 2	Acid 3	Lime	Acid 0	Acid 1	Acid 2	Acid 3	Lime
	Exchangeable aluminium Al µg/g d.w.									
Humus	90.4	104.4	130.5	120.2	2.7	50.9	84.9	59.0	55.2	4.2
Mineral soil										
0 - 5 cm	245.7	256.3	299.1	290.4	41.0	199.4	224.6	198.1	252.3	48.6
5- 10 "	183.7	206.8	209.1	189.7	120.6	214.3	280.3	284.1	220.6	138.5
10- 20 "	43.9	38.7	48.9	46.5	44.5	57.4	84.4	87.7	71.0	34.2
	Extractable sulphate S µg/g d.w.									
Mineral soil										
0 - 5 cm	3.0	8.5	23.7	15.9	3.5	17.3	15.7	7.7	15.0	6.6
5 -10 "	36.3	41.5	72.7	85.6	27.6	77.2	38.0	60.7	108.7	57.0
10 -20 "	97.3	112.2	129.9	167.1	93.5	141.0	184.5	232.6	248.7	164.1

Table 8.6. Expt E57, Norrliden, total carbon (C % d.w.), total nitrogen (N % d.w.) and carbon/nitrogen ratio in soil layers from differently treated plots.Sampling in June 1985. Means of three replicate plots.For significance tests (acid, lime and NPK effects,and interactions), see Table 3.2.

	Treatment									
	- N P K					+ N P K				
Soil layer	Acid 0	Acid 1	Acid 2	Acid 3	Lime	Acid 0	Acid 1	Acid 2	Acid 3	Lime
	Total carbon C % d.w.									
Humus	41.3	42.4	43.0	42.2	29.0	43.4	44.7	45.2	45.6	35.7
Mineral soil										
0 - 5 cm	1.36	1.43	1.37	1.58	1.49	1.59	1.49	1.50	1.48	1.67
5 -10 "	1.19	1.14	1.46	1.17	1.04	1.40	1.04	1.22	1.30	1.35
10 -20 "	1.15	0.88	1.05	1.01	0.93	1.10	1.16	1.26	1.00	1.05
	Total nitrogen N % d.w.									
Humus	1.10	1.21	1.16	1.16	0.76	1.33	1.26	1.35	1.24	1.23
Mineral soil										
0 - 5 cm	0.046	0.050	0.048	0.057	0.045	0.056	0.053	0.057	0.058	0.065
5 -10 "	0.049	0.040	0.052	0.045	0.042	0.058	0.043	0.047	0.049	0.054
10 -20 "	0.049	0.034	0.042	0.040	0.038	0.047	0.048	0.051	0.042	0.047
	Carbon/nitrogen ratio									
Humus	37.6	35.2	37.3	36.8	38.6	32.8	35.8	33.5	37.2	29.2
Mineral soil										
0 - 5 cm	29.5	29.0	28.1	27.4	33.3	28.3	28.4	26.4	25.5	25.7
5 -10 "	24.0	28.8	28.1	25.8	24.9	23.9	25.9	25.9	25.9	24.9
10 -20 "	23.5	26.1	24.9	25.3	24.3	23.4	24.4	24.8	23.8	22.4

Table 8.7. Expt E57, Norrliden. Dry weight of humus layer and mineral soil (fraction < 2 mm) in 10^3 kg/ha. Values with the same subscript are not statistically different at the 5 per cent level. Means of three replicate plots. Dry weight for mineral soil is estimated from the stoniness index (see Fig 2.5).

Soil layer	Treatment									
	− N P K					+ N P K				
	Ac 0	Ac 1	Ac 2	Ac 3	Lime	Ac 0	Ac 1	Ac 2	Ac 3	Lime
Humus	26.3_{b}	27.8_{ab}	28.6_{ab}	28.1_{ab}	34.2_{a}	27.9_{ab}	32.5_{a}	32.5_{a}	32.7_{a}	32.2_{a}
Mineral soil 0 - 5 cm	417.0_{ab}	431.3_{ab}	406.0_{b}	401.7_{b}	428.3_{ab}	416.0_{ab}	459.7_{a}	409.7_{b}	419.7_{ab}	419.0_{ab}
5 -10 "	417.0_{ab}	431.3_{ab}	406.0_{b}	401.7_{b}	428.3_{ab}	416.0_{ab}	459.7_{a}	409.7_{b}	419.7_{ab}	419.0_{ab}
10 -20 "	834.0_{ab}	862.6_{ab}	812.0_{b}	803.4_{b}	856.6_{ab}	832.0_{ab}	919.3_{a}	819.3_{b}	839.3_{ab}	838.0_{ab}
Sum of mineral soil layers	1668.0	1725.2	1624.0	1606.7	1681.9	1664.0	1838.0	1638.7	1678.7	1676.0
Total sum (all layers)	1694.3	1753.0	1652.6	1634.8	1716.1	1691.9	1870.5	1671.2	1711.4	1708.2

Table 8.8. Expt E57, Norrliden. Quantity of total carbon (in 10^3 kg/ha) in soil layers from differently treated plots. Sampling in June 1985 . Means of three replicate plots.For significance tests (acid,lime and NPK effects, and interactions), see Table 3.3.

Soil layer	Treatment									
	- N P K					+ N P K				
	Ac 0	Ac 1	Ac 2	Ac 3	Lime	Ac 0	Ac 1	Ac 2	Ac 3	Lime
	Total carbon, C 10^3 kg/ha									
Humus	10.1	11.8	12.2	11.8	9.8	12.2	14.5	15.2	14.9	11.5
Mineral soil 0 -20 cm	20.2	18.7	20.0	19.2	19.1	21.5	22.4	20.4	20.0	21.4
	Total nitrogen, N kg/ha									
humus	270	337	329	323	254	375	411	455	410	394
Mineral soil 0 - 20 cm	808	674	748	734	692	866	878	845	806	897

Table 8.9. Expt E57, Norrliden. Quantity of exchangeable calcium, magnesium, potassium and sodium (Ca, Mg, K and Na keq/ha) in soil layers from differently treated plots. Sampling in June 1985. Means of three replicate plots. For significance tests (acid,lime and NPK effects, and interactions), see Table 3.3.

Soil layer	Treatment									
	- N P K					+ N P K				
	Ac 0	Ac 1	Ac 2	Ac 3	Lime	Ac 0	Ac 1	Ac 2	Ac 3	Lime
					Calcium, Ca keq/ha					
Humus	1.5	2.0	2.6	1.8	19.4	3.0	2.7	3.0	3.0	15.4
Mineral soil 0 - 20 cm	8.6	7.8	5.9	3.7	30.1	7.4	6.4	5.2	4.7	24.5
					Magnesium, Mg keq/ha					
Humus	0.3	0.4	0.4	0.2	0,4	0.2	0.3	0.3	0.2	0.4
Mineral soil 0 - 20 cm	1.3	0.8	0.6	0.6	1.3	0.6	0.6	0.7	0.5	0.8
					Potassium, K keq/ha					
Humus	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Mineral soil 0 - 20 cm	1.8	1.6	2.4	1.4	1.8	3.4	3.6	3.7	3.2	3.2
					Sodium, Na keq/ha					
Humus	0.02	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.03
Mineral soil 0 - 20 cm	0.43	0.48	0.41	0.35	0.36	0.34	0.30	0.45	0.29	0.31

Table 8.10. Expt E57, Norrliden, quantity of titratable acidity (H^+ keq/ha), exchangeable aluminium (Al_{KCl} kg/ha) and extractable sulphate (SO_4-S kg/ha) in soil layers from differently treated plots. Sampling in June 1985. Means of three replicate plots. For significance tests (acid, lime and NPK effects, and interactions) see Table 3.3.

Soil layer	Treatment									
	− N P K					+ N P K				
	Ac 0	Ac 1	Ac 2	Ac 3	Lime	Ac 0	Ac 1	Ac 2	Ac 3	Lime
	H^+ keq/ha									
Humus	7.0	9.3	12.6	9.1	<0.00004	7.6	10.6	9.5	10.4	2.5
Mineral soil 0 – 20 cm	48.5	49.7	54.7	57.4	32.5	62.4	65.3	69.7	63.0	46.7
	Aluminium, Al kg/ha									
Humus	3.22	2.91	3.80	3.60	0.07	1.41	2.63	1.92	1.74	0.14
Mineral soil 0 – 20 cm	215.80	234.01	245.32	232.93	107.74	216.88	309.44	268.83	256.62	107.06
	Sulphate, SO_4-S kg/ha									
Mineral soil 0 – 20 cm	97.33	117.83	144.99	173.41	93.23	157.46	194.34	219.08	280.72	164.76

Table 8.11. Expt **E57, Norrliden.** Stand and growth data. All values are means of three replicate plots.

		Treatment									
		- N P K					+ N P K				
	Year	Acid 0	Acid 1	Acid 2	Acid 3	Lime	Acid 0	Acid 1	Acid 2	Acid 3	Lime
Diameter (cm)	1971	7.5	6.2	7.4	7.7	6.6	7.6	6.9	8.0	7.7	7.3
	1984	12.3	12.7	12.8	13.3	12.0	14.5	14.1	14.6	14.0	14.3
Mean height (m)	1971	5.0	4.4	4.9	5.2	4.6	5.0	4.6	5.1	5.2	4.8
	1984	10.9	10.3	11.1	11.2	10.5	10.4	10.3	10.4	10.3	9.9
Basal area	1971	10.0	6.0	8.8	9.7	7.5	9.6	7.6	10.5	9.8	8.7
(m^2/ha)	1984	26.1	21.7	25.9	28.1	22.6	31.6	28.8	31.4	30.6	30.6
Basal area increment (m^2/ha/year)	72–84	1.24	1.22	1.33	1.42	1.18	1.79	1.69	1.70	1.63	1.73
	80–84	1.03	1.05	1.10	1.12	0.99	1.28	1.22	1.06	1.12	1.22
Stem volume (m^3/ha)	1971	34.6	19.4	30.3	33.8	25.3	32.7	24.9	36.5	34.3	28.9
	1984	150.4	119.0	151.0	164.7	126.9	173.5	157.4	173.8	167.9	162.5
Stem volume increment (m^3/ha/year)	72–84	8.91	7.71	9.29	10.04	7.85	11.25	10.47	11.00	10.43	10.46
Total volume production (m^3 /ha)	72–84	115.8	100.2	120.8	130.6	102.1	146.3	136.1	143.0	135.6	136.0
Number of stems/ha	1971	2100	1725	1925	1925	1975	1975	1875	2000	1975	1950
	1984	2100	1625	1900	1925	1925	1825	1725	1825	1875	1850

Table 8.12. Expt E42, Lisselbo, pH-values(measured in water) in different soil layers from various plots sampled in three different years. The first plot in each pair belongs to Block No 9 and the second one to Block No.10.

Treatment	plot No	Sampling 1971 May	1976 May	1976 October	1985 June	Remarks
			Humus layer			
Control	55	3.9	3.9	3.9	-	No clear time trend
	60	3.9	4.0	3.8	-	
Irrigation	73	-	4.1	3.9	4.1	No clear time trend
	65	3.9	4.2	3.8	4.0	
Acid 1	63	-	3.9	3.6	4.4	Recovery in 1985
	72	4.0	3.8	3.7	4.1	
Acid 2	69	-	3.8	3.4	4.2	Recovery in 1985
	57	3.8	3.7	3.9	4.2	
Lime	62	6.3	6.6	6.2	6.0	Slight decrease with
	58	6.6	6.7	6.2	6.0	time
N P K	66	4.4	4.2	4.1	4.3	No clear time trend
	61	4.1	4.2	4.0	4.4	
" +Irrig.	54	4.0	-	3.7	-	Too few observations
	59	4.0	-	4.0	-	
" + Ac 1	70	4.0	3.9	3.9	4.3	Increase in 1985
	64	3.9	3.9	3.8	4.2	
" + Ac 2	67	-	3.9	3.7	4.4	Increase in 1985
	56	-	3.7	3.9	4.4	
" + lime	68	5.0	6.0	5.8	5.7	No clear time trend
	71	4.8	5.5	5.4	5.2	
			Mineral soil,0 - 5 cm			
Control	55	-	4.3	4.1	-	Too few observations
	50	4.2	4.7	4.4	-	
Irrigation	73	-	4.6	4.4	4.6	No clear time trend
	65	-	4.6	4.1	4.2	
Acid 1	63	-	4.3	4.1	4.5	No clear time trend
	72	-	4.4	4.1	4.4	
Acid 2	69	-	4.3	3.6	4.3	No clear time trend
	57	-	4.4	3.8	4.3	

Table 8.12. Expt E42, Lisselbo, ... continued

Lime	62	4.8	-	5.3	5.4	Increase from 1971
	58	4.4	-	5.2	5.0	
N P K	66	4.4	-	4.1	4.2	No time trend
	61	4.3	-	4.2	4.3	
" + Irrig.	54	-	-	4.0	-	Too few observations
	59	-	-	3.9	-	
" + Ac 1	70	-	4.3	3.8	4.1	No clear time trend
	64	-	4.3	3.7	4.0	
" + Ac 2	67	-	4.3	3.7	4.4	No clear time trend
	56	-	4.4	3.8	4.1	
" + Lime	68	4.8	-	4.7	5.1	No clear time trend
	71	4.7	-	4.4	4.8	
			Mineral soil, 5 - 10 cm			
Control	55	-	4.8	4.8	-	Too few values
	60	-	4.8	4.9	-	
Irrigation	73	-	4.7	4.4	4.9	No time trend
	65	-	4.7	4.9	4.5	
Acid 1	63	-	4.6	4.6	4.7	No time trend
	72	-	4.7	4.4	4.7	
Acid 2	69	-	4.3	4.5	4.5	No time trend
	57	-	4.3	4.1	4.7	
Lime	62	-	-	5.5	5.5	Too few values
	58	-	-	5.3	5.2	
N P K	66	-	-	4.4	4.6	Too few values
	61	-	-	4.5	4.6	
" + Irrig.	54	-	-	4.1	-	Too few values
	59	-	-	4.1	-	
" + Ac 1	70	-	4.4	4.3	4.4	No time trend
	64	-	4.4	3.9	4.4	
" + Ac 2	67	-	4.3	4.2	4.6	No time trend
	56	-	4.3	4.1	4.5	
" + Lime	68	-	-	4.6	5.1	Too few values
	71	-	-	4.5	5.0	

Table 8.13. Expt E42, Lisselbo, pH-levels, degree of base saturation (%), cation exchange capacity and titratable acidity (µeq/g d.w.) in soil layers from differently treated plots. Sampling in June 1985. Treatment "Ac0" (-NPK) stands for means of plots 65 and 73, which received a total of 420 mm irrigation water 1970-76. (see text for further comments). Means of two replicate plot.

soil layer	Treatment							
	- N P K				+ N P K			
	"Ac 0"	Ac 1	Ac 2	lime	Ac 0	Ac 1	Ac 2	lime
	a) pH-values in water							
Humus	4.0	4.2	4.2	6.0	4.3	4.3	4.4	5.5
Mineral soil								
0-5 cm	4.4	4.5	4.3	5.2	4.2	4.0	4.3	4.9
5-10 "	4.7	4.7	4.6	5.3	4.6	4.4	4.5	5.0
10-20 "	4.8	4.7	4.6	5.3	4.7	4.5	4.4	5.2
	b) degree of base saturation %, measured at pH = 7							
Humus	14.3	13.0	11.6	88.1	20.8	19.5	16.1	71.4
Mineral soil								
0 - 5 cm	5.0	5.6	4.4	41.6	10.7	11.4	9.1	14.9
5 -10 "	3.0	3.2	2.7	21.6	7.7	7.1	4.3	22.0
10 -20 "	3.6	3.6	3.3	22.5	5.1	4.8	4.1	21.0
	c) cation exchange capacity, µeq/g d.w.							
Humus	415.9	306.7	307.6	452.4	311.5	368.1	284.7	417.1
Mineral soil								
0 - 5 cm	44.7	44.5	45.6	46.6	58.4	72.7	48.6	58.7
5 -10 "	30.5	29.8	29.2	29.6	39.2	54.0	30.4	45.7
10 -20 "	20.8	18.3	18.4	16.8	22.5	27.4	18.1	23.1
	d) titratable acidity, µeq/g d. w.							
Humus	356.3	267.4	272.0	53.8	296.6	296.2	238.8	129.6
Mineral soil								
0-5 cm	42,2	42.1	43.6	26.7	52.1	64.6	44.2	36.6
5-10 "	29.6	28.8	28.4	22.9	36.3	50.1	29.1	35.6
10-20 "	20.2	17.6	17.8	13.0	21.4	26.1	17.4	18.2

Table 8.14. Expt E42, Lisselbo, exchangeable calcium, exchangeable magnesium, exchangeable potassium and exchangeable sodium µeq/g d.w.in soil layers from differently treated plots. Sampling in June 1985. For treatment "Ac0", see Table 8.13. Means of two replicate plots.

Soil layer	Treatment							
	- N P K				+ N P K			
	"Ac 0"	Ac 1	Ac 2	lime	Ac 0	Ac 1	Ac 2	lime
	a) exchangeable calcium **Ca** µeq/g d.w.							
Humus	45.1	28.9	24.5	379.6	57.5	63.5	38.3	272.2
Mineral soil								
0 - 5 cm	1.2	1.3	1.0	17.6	4.7	6.3	3.0	20.4
5 -10 "	0.4	0.4	0.2	5.7	2.0	2.6	0.6	9.2
10 -20 "	0.3	0.2	0.2	3.3	0.6	0.7	0.3	4.3
	b) exchangeable magnesium **Mg** µeq/g d.w.							
Humus	9.10	6.66	7.59	14.82	4.30	4.76	4.34	11.44
Mineral soil								
0 - 5 cm	0.35	0.36	0.42	1.03	0.50	0.66	0.46	0.96
5 -10 "	0.14	0.14	0.14	0.36	0.26	0.28	0.13	0.40
10 -20 "	0.09	0.08	0.08	0.13	0.10	0.11	0.07	0.13
	c) exchangeable potassium **K** µeq/g d.w.							
Humus	4.50	3.06	3.11	3.60	2.79	2.83	2.98	3.35
Mineral soil								
0-5 cm	0.54	0.57	0.47	0.69	0.92	1.08	0.86	0.60
5-10 "	0.29	0.34	0.38	0.53	0.58	0.68	0.40	0.45
10-20 "	0.24	0.26	0.28	0.26	0.32	0.44	0.32	0.30
	d) exchangeable sodium **Na** µeq/g d.w.							
Humus	0.92	0.69	0.46	0.59	0.32	0.83	0.37	0.56
Mineral soil								
0-5 cm	0.13	0.17	0.12	0.18	0.14	0.16	0.11	0.16
5-10 "	0.09	0.09	0.07	0.13	0.09	0.25	0.14	0.11
10-20 "	0.07	0.08	0.08	0.09	0.16	0.07	0.06	0.10

Table 8.15. Expt E42, Lisselbo, exchangeable aluminium (Al-KCl µg/g d.w.) and concentration of sulphate-S (S µg/g d.w.) in soil layers from differently treated plots. Sampling in June 1985. a) Means of two replicate plots. For treatment "Ac0",see Table 4.3

Soil layer	Treatment							
	- N P K				+ N P K			
	"Ac 0"	Ac 1	Ac 2	lime	Ac 0	Ac 1	Ac 2	lime
a) exchangeable aluminium **Al** µg/g d.w.								
Humus	392.4	273.4	274.0	<0.01	116.8	111.3	122.2	30.7
Mineral soil								
0 - 5 cm	172.0	211.1	202.2	96.2	189.6	171.8	184.6	58.4
5 -10 "	86.8	87.0	91.2	55.5	141.1	72.0	104.3	57.0
10 -20 "	31.7	28.0	51.9	30.2	67.5	61.4	49.2	47.0
b) extractable sulphate **S** µg/g d.w.								
Mineral soil								
0 - 5 cm	0.6	-	3.0	-	5.7	-	5.3	-
	4.8	-	4.8	-	3.0	-	2.9	-
5 - 10 "	15.8	-	18.9	-	15.0	-	28.1	-
	26.4	-	23.3	-	10.4	-	30.0	-
10 - 20 "	18.6	-	40.6	-	26.0	-	43.4	-
	32.6	-	45.0	-	30.4	-	62.2	-

Table 8.16. Expt E42, Lisselbo, total carbon (C % d.w.), total nitrogen (N % d.w.) and carbon/nitrogen ratio (C/N) in soil layers from differently treated plots. Sampling in June 1985.For treatment "Ac0" see Table 8.13. Means of two replicate plots.

soil layer	Treatment							
	- N P K				+ N P K			
	"Ac 0"	Ac 1	Ac 2	lime	Ac 0	Ac 1	Ac 2	lime
	a) total carbon **C** % d.w.							
Humus	32.92	31.04	23.70	21.90	31.39	38.35	26.74	29.86
Mineral soil								
0 - 5 cm	1.59	1.58	1.67	1.42	2.06	2.16	2.06	1.62
5 -10 "	0.92	1.24	1.15	0.88	1.22	1.69	0.96	0.98
10 -20 "	0.73	0.56	0.58	0.68	0.76	0.87	0.58	0.64
	b) total nitrogen **N** % d.w.							
Humus	0.96	0.91	0.70	0.66	0.96	1.14	0.83	0.92
Mineral soil								
0 - 5 cm	0.048	0.045	0.049	0.040	0.062	0.068	0.063	0.049
5 -10 "	0.028	0.033	0.033	0.025	0.038	0.052	0.028	0.028
10 -20 "	0.022	0.018	0.016	0.023	0.025	0.026	0.020	0.020
	c) carbon/nitrogen ratio **C/N**							
Humus	34.3	34.1	33.9	33.2	32.7	33.6	32.2	32.5
Mineral soil								
0 - 5 cm	33.1	35.1	34.1	35.5	33.2	31.8	32.7	33.1
5 -10 "	32.8	37.6	34.8	35.2	32.1	32.5	34.3	35.0
10 -20 "	33.2	31.1	36.2	29.6	30.4	33.5	29.0	32.0

Table 8.17. Expt E42, Lisselbo, Stoniness index, Si_{30cm}, and dry weight of humus layer and mineral soil fraction < 2 mm in 10^3 kg/ha. Dry weight for mineral soil is estimated from stoniness index (see Fig 2.5). Sampling in June 1985.

		Treatment								
				- N P K			+ N P K			
Soil layer	Block	0	"Ac 0"	Ac 1	Ac 2	Lime	Ac 0	Ac 1	Ac 2	Lime
					Plot No					
	09	55	73	63	69	62	66	70	67	68
	10	60	65	72	57	58	61	64	56	71
					Stoniness index, Si_{30cm}					
	09	11	30	27	23	30	30	21	30	30
	10	10	20	30	30	29	30	20	30	16
					Dry weight metric tons/ha					
Humus	09	55.9	37.1	45.7	39.5	42.4	49.1	56.0	48.0	43.5
	10	44.1	42.6	34.4	40.4	40.9	52.9	44.5	60.8	44.3
	mean	50.0	39.8	40.0	40.0	41.6	51.0	50.2	54.4	43.9
Mineral soil										
0 - 5 cm	09	242	482	444	394	482	482	368	482	482
	10	230	356	482	482	469	482	356	482	306
5 -10 "	09	242	482	444	394	482	482	368	482	482
	10	230	356	482	482	469	482	356	482	306
10 -20 "	09	485	964	888	788	964	964	736	964	964
	10	460	712	964	964	938	964	712	964	612
Sum of mineral soil layers (mean)		945	1676	1852	1752	1902	1928	1448	1928	1576

Table 8.18. Expt **E42,** Lisselbo, quantity of total carbon (in 10^3 kg/ha) and total nitrogen (N kg/ha) in soil layers from differently treated plots. Sampling in June 1985. Upper line in each pair: block 9: lower line: block 10.

Soil layer	Treatment							
	"Ac 0"	- N P K Ac 1	Ac 2	Lime	Ac 0	+ N P K Ac 1	Ac 2	Lime
				Total carbon C 10^3 kg/ha				
Humus	11.4	15.0	9.30	11.01	17.83	21.78	10.22	13.23
	14.9	10.1	9.64	7.30	14.00	16.82	19.57	13.85
Mineral soil 0 - 20 cm	16.39	14.79	15.36	20.34	28.38	19.10	17.88	16.35
	16.20	20.54	19.52	13.74	20.24	21.40	21.82	-
				Total nitrogen N kg/ha				
Humus	363.6	438.7	276.5	322.2	530.3	616.0	297.6	395.9
	430.3	295.8	278.8	225.0	444.4	520.7	601.9	412.0
Mineral soil 0 - 20 cm	551.0	435.0	441.2	612.5	819.5	600.1	592.8	539.9
	505.5	587.8	544.7	412.7	583.9	622.5	705.0	-

Table 8.19. Expt **E42,** Lisselbo, quantity of titratable acidity H^+ keq/ha and cation exchange capacity CEC keq/ha in soil layers from differently treated plots. Sampling in June 1985. Upper line in each pair: block 9: lower line: block 10.

Soil layer	Treatment							
		- N P K			+ N P K			
	"Ac 0"	Ac 1	Ac 2	Lime	Ac 0	Ac 1	Ac 2	Lime
	titratable acidity H^+ keq/ha							
Humus	13.1	10.9	10.7	2.54	12.4	17.6	10.1	2.20
	15.1	10.2	11.0	1.96	12.7	12.4	16.2	9.24
Mineral soil 0 - 20 cm	42.5	40.4	43.1	35.7	70.9	60.0	52.7	41.7
	48.6	58.1	50.0	36.2	55.6	60.7	51.4	40.0
	cation exchange capacity CEC keq/ha							
Humus	15.3	12.9	12.1	19.3	15.5	22.1	12.0	14.9
	17.9	11.4	12.5	18.4	16.3	15.2	19.5	21.8
Mineral soil 0 - 20 cm	44.6	42.9	44.6	56.2	76.3	66.0	55.9	59.1
	50.2	42.9	53.0	47.9	61.3	65.4	55.2	54.6

Table 8.20. Expt **E42,** Lisselbo, quantity of exchangeable calcium and magnesium (Ca and Mg, keq/ha) in soil layers from differently treated plots. Sampling in June 1985. Upper line in each pair: block 9: lower line: block 10.

Soil layer	Treatment							
		- N P K				+ N P K		
	"Ac 0"	Ac 1	Ac 2	Lime	Ac 0	Ac 1	Ac 2	Lime
				Exchangeable calcium Ca keq/ha				
Humus	1.56	1.53	0.95	15.9	2.69	3.93	1.59	12.1
	2.05	0.83	1.01	15.7	3.18	2.53	2.64	11.8
Mineral soil 0 - 20 cm	1.01	1.07	0.66	18.61	3.80	4.17	1.83	15.60
	0.76	0.93	0.69	9.87	3.72	3.34	2.24	12.83
				Exchangeable magnesium Mg keq/ha				
Humus	0.30	0.34	0.25	0.64	0.23	0.31	0.16	0.46
	0.43	0.20	0.36	0.60	0.21	0.18	0.33	0.55
Mineral soil 0 - 20 cm	0.28	0.25	0.26	0.93	0.43	0.44	0.26	0.83
	0.36	0.37	0.39	0.65	0.51	0.40	0.45	0.47

Table 8.21. Expt **E42**, Lisselbo, quantity of exchangeable aluminium, Al kg/ha, and exchangeable potassium, K keq/ha, in soil layers from differently treated plots. Sampling in June 1985. Upper line in each pair: block 9: lower line: block 10.

Soil layer	Treatment							
	- N P K				+ N P K			
	"Ac 0"	Ac 1	Ac 2	Lime	Ac 0	Ac 1	Ac 2	Lime
	Exchangeable aluminium Al kg/ha							
Humus	16.93	6.33	15.26	<0.002	5.31	7.15	6.77	1.85
	13.99	14.04	6.53	<0.002	6.63	4.22	6.29	0.84
Mineral soil 0 - 20 cm	122.95	160.51	148.11	61.56	238.88	128.37	163.02	97.85
	139.27	166.96	201.73	130.29	210.10	136.88	209.87	65.97
	Exchangeable potassium K keq/ha							
Humus	0.15	0.13	0.12	0.15	0.14	0.18	0.10	0.12
	0.21	0.12	0.13	0.15	0.15	0.11	0.23	0.17
Mineral soil 0 - 20 cm	0.58	0.59	0.53	0.70	0.96	1.09	0.92	0.78
	0.52	0.73	0.69	0.95	1.12	0.79	0.91	0.51

Table 8.22. Expt **E42, Lisselbo.** Stand and growth data.

			Treatment								
				-NPK				+NPK			
	Block	Year	Control	Irrigation	Acid 1	Acid 2	Lime	Acid 0	Irrigation	Acid 1	Acid 2
Plots No	9		55	73	63	69	62	66	54	70	67
	10		60	65	72	57	58	61	59	64	56
Diameter cm	9	1971	4.5	4.5	5.2	4.6	4.4	5.6	4.9	6.0	5.8
	10		5.8	5.7	5.0	5.6	4.9	5.8	6.4	5.6	5.4
	9	1985	10.6	11.2	11.8	11.4	11.3	13.1	12.5	14.1	13.6
	10		12 0	11.9	11.3	12.3	11.6	13.9	13.9	12.9	13.0
Bjørgung index $n.h^2$	9	1968	42.7	38.5	40.4	38.6	37.2	39.6	34.4	36.3	36.7
	10		61.2	54.3	47.1	53.4	39.5	48.6	48.7	39.6	35.2
Mean height m	9	1968	2.4	2.3	2.4	2.3	2.2	2.3	2.1	2.3	2.3
	10		2.8	2.8	2.5	2.7	2.4	2.6	2.5	2.3	2.2
	9	1971	3.4	3.5	3.5	3.3	3.3	3.4	3.1	3.4	3.4
	10		3.9	3.9	3.7	3.8	3.6	3.6	3.8	3.3	3.3
	9	1985	8.6	8.8	8.8	8.5	8.6	8.3	8.8	8.4	8.8
	10		9.2	9.7	9.0	9.8	9.3	9.1	8.9	8.0	8.5
Basal area m^2 /ha	9	1971	2.93	2.52	2.68	2.63	2.44	3.81	3.35	3.87	3.57
	10		4.46	3.56	2.97	3.87	2.34	4.49	4.75	3.71	3.57
	9	1985	13.91	14.66	13.27	14.68	14.65	20.09	20.60	19.87	19.89
	10		13.84	15.20	14.37	18.51	12.63	22.21	22.60	18.86	19.08
Basal area increment m^2/ha/year	9	72–77	0.87	0.97	0.82	0.94	0.86	1.43	1.69	1.41	1.41
	10		1.07	1.04	0.87	1.16	0.75	1.55	1.84	1.35	1.35
	9	78–85	0.72	0.79	0.71	0.80	0.89	0.97	0.89	0.95	0.98
	10		0.87	0.68	0.77	0.96	0.72	1.05	0.85	0.88	0.93
Stem volume increment m^3 /ha	9	72–77	3.54	4.14	3.46	3.71	3.38	5.09	6.49	5.38	5.24
	10		4.85	4.71	3.77	5.21	3.14	5.88	7.58	4.97	5.96
	9	78–85	4.71	5.14	4.68	5.00	5.58	6.50	6.33	6.12	6.49
	10		6.10	4.98	5.18	6.94	4.80	7.60	6.23	5.34	6.37
Total volume production m^3 /ha	9	71–85	58.93	65.89	58.15	62.23	64.89	82.51	89.63	81.25	83.39
	10		77.89	68.12	64.03	86.77	57.25	96.04	95.31	72.49	80.75
Number of stems/ha	9	1968	1475	1370	1150	1375	1400	1350	1560	1200	1225
	10		1525	1275	1375	1400	1100	1400	1435	1350	1350
Number of stems/ha	9	1985	1425	1270	1150	1275	1275	1075	1435	1075	1050
	10		1525	1245	1350	1350	950	1150	1305	1075	1375

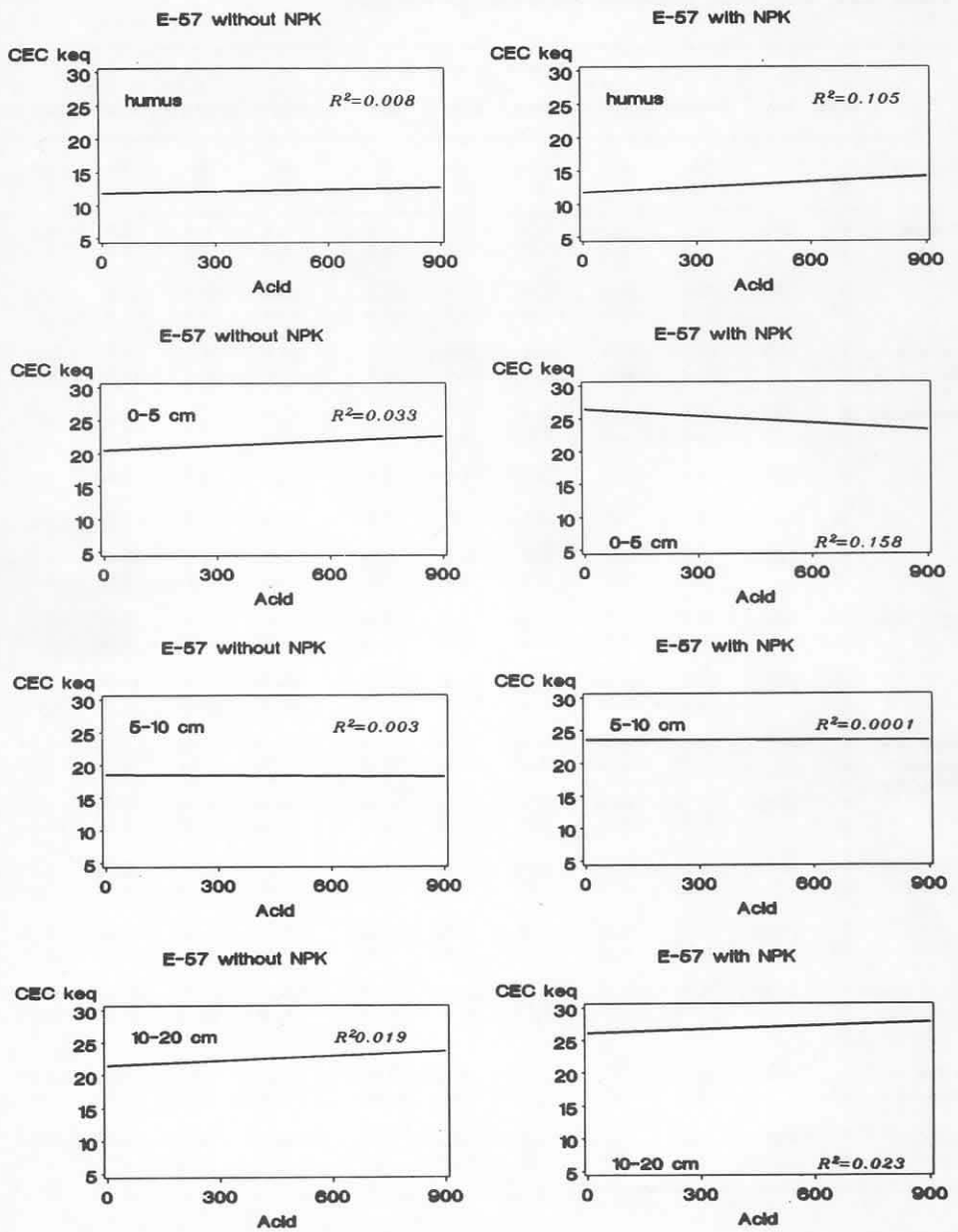

Fig. 8.2. Cation exchange capacity (CEC, in keq per ha) in humus layer and mineral soil horizons plotted against acid application in Experiment E 57.

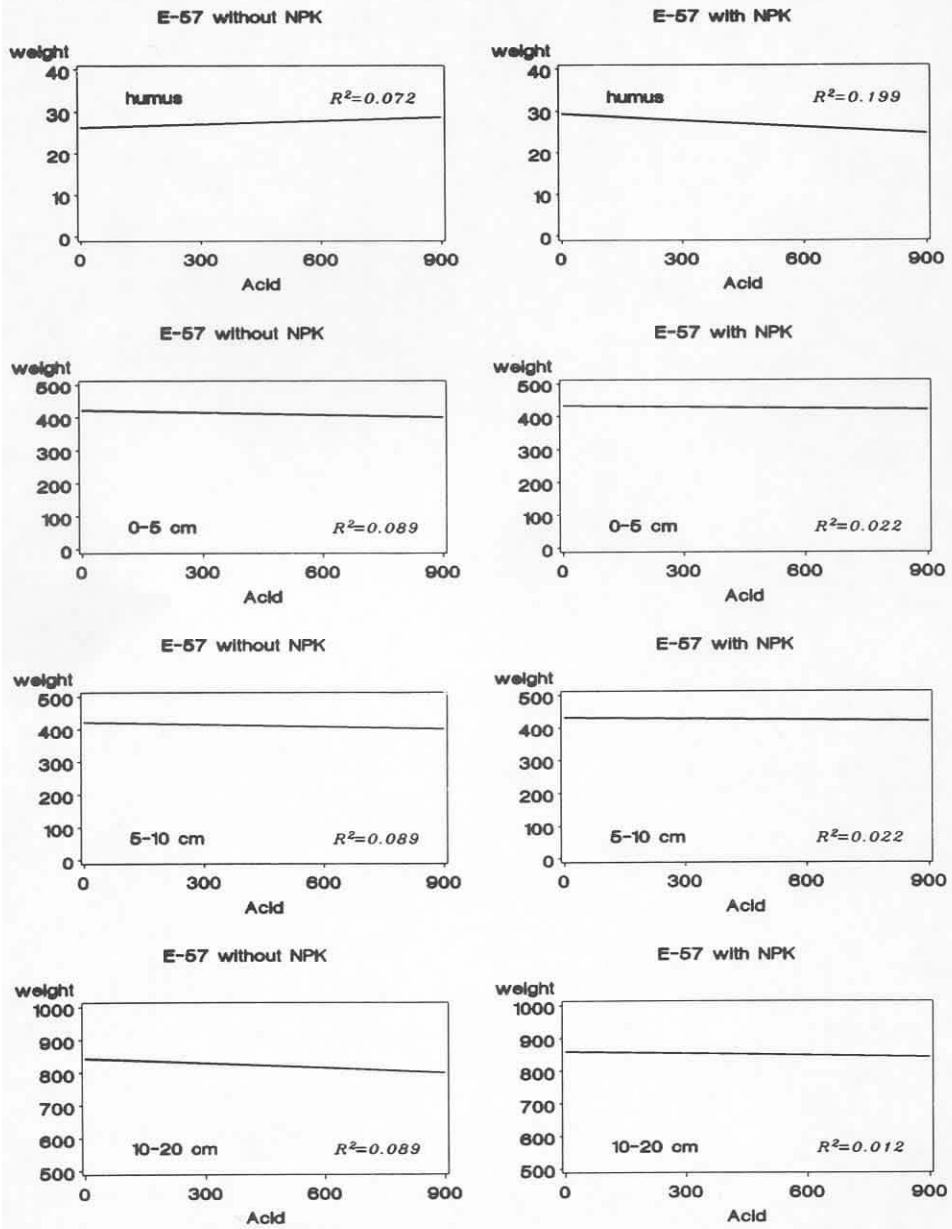

Fig. 8.1. Dry weight of humus layer and of the fraction <2 mm in mineral soil horizons, metric tons per ha, plotted against acid application in Experiment E 57. Humus weights from auger samplings, mineral soil weights calculated from the stoniness index, see text.